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CALIBRATION OF LANDSAT-4 TM REFLECTIVE BANDS  
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CHARACTERIZATION OF RADIOMETRIC CALIBRATION  
OF LANDSAT-4 TM REFLECTIVE BANDS



J. L. Barker

National Aeronautics and Space Administration  
Goddard Space Flight Center  
Greenbelt, Maryland 20771

R. B. Abrams, D. L. Ball, and K. C. Leung

Computer Sciences Corporation  
8728 Colesville Road  
Silver Spring, Maryland 20910



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OF LANDSAT-4 TM REFLECTIVE BANDS

ABSTRACT

Absolute radiometric calibration of known accuracy is important for several applications of Landsat-4 Thematic Mapper (TM) data. This paper examines prelaunch and postlaunch internal calibrator, image, and background data to characterize the radiometric performance of the Landsat-4 TM and to recommend improved procedures for radiometric calibration. All but two channels (band 2, channel 4; band 5, channel 3) have behaved normally. Gain changes relative to a postlaunch reference (scene ID 40109-15140) for channels within a band vary within 0.5 percent as a group. The primary focal plane channels show an initial decrease in gain of 6 percent in bands 1 and 2, 8 percent in band 3, and 3 percent in band 4 during the first 70 days following launch, and thereafter show gain changes of 1 percent or less. Instrument gain for channels in the cold focal plane oscillates. In band 5, the maximum peak-to-peak amplitude is 7 percent and the frequency is approximately 55 days, while in band 7 the amplitude is 5 percent and the frequency is 75 days. Noise in background and image data ranges from 0.5 to 1.7 counts. Average differences in forward and reverse image data indicate a need for separate calibration processing of forward and reverse scans. Precision is improved by increasing the pulse integration width from 31 to 41 minor frames, depending on the band.

KEYWORDS: radiometric performance, internal calibrator stability, channel precision, channel stability, noise, parametric adjustments in calibration, Thematic Mapper, and Landsat-4.

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## INTRODUCTION

Scientists concerned with relating ground-measured variables and atmospheric characteristics to measurements of spectral radiance from satellites need absolute radiometric values for Thematic Mapper (TM) Landsat-4 data. Absolute radiometric calibrations of known accuracy are essential to understand and characterize the physical properties and interactions causing radiance variations, to test theoretical models, to perform arithmetic spectral transforms such as those used to determine within-scene atmospheric corrections, and to compare TM data with laboratory and field observations. Furthermore, image applications in areas such as forestry and geology are aided by knowledge of absolute radiance. Such knowledge would lead to an understanding of the innate bidirectional reflectance properties of the target. With absolute radiance values, signatures could be extended between scenes. With absolute radiance values, monitoring and modeling studies could use data covering the same area but collected by instruments on different satellites. This paper characterizes the radiometric performance of the TM.

The emphasis of this paper is on postlaunch radiometric characterization of the Landsat-4 TM sensor system, especially the precision of the internal calibration (IC) system and its variation with time. Only data for the reflective bands are presented here. Lansing and Barker (1984) discuss procedures and results for the thermal band. A description of the TM calibration subsystem and the prelaunch and post-launch radiometric calibration procedures in Barker, Abrams, et al., 1984, provides background to this paper. Absolute sensitivities and offsets for each of the TM reflective band channels and spectral radiances for the IC states are presented in Barker, Ball, et al., 1984, which describes the results of the prelaunch absolute radiometric calibration. TM digital image products are described and characterized in Barker, Gunther, et al., 1984.

Several methods of calibrating TM sensor data are available (Barker, 1984). If the sensor channels are more stable with time than the IC system, prelaunch nominal gains and offsets can be used directly. Alternatively, the IC system can be used to determine gains and offsets. In either case, gains and offsets for channels in a band can be modified by histogram normalization. This paper provides insight as to the best calibration procedure to use.

## ANALYSIS OF RADIOMETRIC PERFORMANCE

### STABILITY OF THE IC SYSTEM

The separation of IC system stability from channel stability ordinarily requires the observation of a known external source, such as the Sun or Moon. Because the TM does not have access to such an external source, another approach must be used. One possibility in evaluating the stability of the IC system involves comparison of the normalized changes in the band-averaged channel response to the single-lamp IC states (100, 010, and 001<sup>1</sup>). The normalized change in digital counts, NC, is calculated for each combination of single lamp IC state and band using the following equation:

$$NC = \frac{\bar{P}_1 - \bar{P}_2}{\bar{P}_2}$$

where  $\bar{P}_1$  is the average count for a given IC state and band on day 1, and  $\bar{P}_2$  is the count for the same state and band on the reference day, day 2.

In practice, because the odd-numbered detectors in a band are physically separated from the even-numbered ones, separate band averages are computed for the even-numbered and odd-numbered channels. If the IC system is stable between days 1 and 2, the value of NC should depend only on the band; NC should be independent of the IC state.

NC values for nine postlaunch scenes were calculated using two references: (1) a prelaunch vacuum test conducted by the General Electric Company (GE) on March 9, 1982 and (2) the November 2, 1982, postlaunch scene over Washington, D.C. The results, presented in the Appendix (Tables A-1 through A-10), indicate that the relationship of lamp 2 to lamps 1 and 3 has changed relative to prelaunch. For any given band, the NC values for the three lamps with November 2 as the reference are within 0.5 percent of the same value. When prelaunch March 9 data are used as a reference, the NC values for lamps 1 (state 100) and 3 (state 001) have a change in counts within 0.8 percent, and on the average, lamp 2 differs from lamp 1 by 2.2 percent.

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<sup>1</sup>In this paper, the configuration of the IC is represented by three binary numbers that indicate the status of the three IC lamps, e.g., IC state 100 implies that lamp 1 is on and that lamps 2 and 3 are off.

Another approach to evaluating the IC system performance that is essentially independent of the channels is to determine the internal consistency of the IC system. Calibration pulse averages collected from the same channel and scene should be consistent; that is, the following sums should be less than 1 digital count:

$$S(1) = P(110,C) - P(100,C) - P(010,C)$$

$$S(2) = P(101,C) - P(100,C) - P(001,C)$$

$$S(3) = P(011,C) - P(010,C) - P(001,C)$$

$$S(4) = P(111,C) - P(100,C) - P(010,C) - P(001,C)$$

where  $P(1,C)$  is the average net pulse value in digital counts (background subtracted) for each IC level and  $S(1,C)$  is the sum of the IC states. For that channel (C), tables 1 through 4 present values for  $S(1,C)$ ,  $S(2,C)$ ,  $S(3,C)$ , and  $S(4,C)$ . It should be noted that, ignoring  $S_4$  for band 4 (where detector saturation in the 111 IC state is a major factor), the values of all but 12 sums are below one digital count; all sums are below 1-1/2 digital counts.

#### PRELAUNCH SENSOR PERFORMANCE

Prior to launch, nominal gains and offsets for each channel were obtained by external calibration with an integrating sphere under ambient conditions. The Scrounge algorithms for pulse integration, pulse averaging, and regression analysis described in Barker, Abrams, et al. (1984) were used in the external calibration procedure. The detector gains and off-sets were then applied to obtain nominal radiances for each IC state channel combination. The external calibration procedure is described in detail in Barker, Abrams, et al. (1984) and Barker, Ball, et al. (1984).

Prelaunch tests were conducted in February and March of 1982 to compare detector and IC system performance in an ambient environment with performance in a vacuum environment similar to in-orbit conditions. Table 5 lists ambient gain changes relative to vacuum values as measured by the IC system for the primary focal plane channels. It should be noted that the amount and even the direction of the gain shift is different for each bank of detectors (ranging from a 5-percent decrease to a 2-percent increase) and that the gain in ambient conditions decreases relative to the gain in vacuum conditions as the cal-shutter flag temperature increases. Table 6 lists averaged pulse values ( $\bar{P}$ ) in digital counts for the three single-lamp states under ambient and vacuum

TABLE 1

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
 SACRAMENTO, CALIFORNIA DECEMBER 31, 1982  
 SUM (S(1,C)) OF NET IC STATES (110-100-010)

CHANNEL		TM 1	TM 2	TM 3	TM 4	TM 5	TM 7
7	1	-0.75	-0.72	-0.39	-1.03	-0.59	-0.62
	2	-0.71	-0.54	-0.25	-0.51	-0.45	-0.60
	3	-0.73	-0.78	-0.58	-0.93	—	-0.04
	4	-0.38	-0.49	-0.25	-0.56	-0.05	0.00
	5	-0.73	-1.13	-0.47	-0.89	-0.05	-0.06
	6	-0.70	-0.76	-0.42	-0.97	-0.07	-0.10
	7	-0.57	-0.94	-0.59	-1.32	-0.08	0.09
	8	-0.48	-0.44	-0.19	-0.55	0.09	-0.17
	9	-0.67	-0.96	-0.53	-0.83	-0.19	-0.02
	10	-0.71	-0.50	-0.36	-0.81	-0.05	-0.10
	11	-0.70	-0.95	-0.38	-0.98	-0.11	-0.12
	12	-0.54	-0.41	-0.44	-0.97	-0.01	-0.06
	13	-0.56	-1.05	-0.57	-0.96	-0.17	-0.11
	14	-0.64	-0.85	-0.43	-1.49	0.05	-0.05
	15	-0.85	-0.99	-0.67	-0.41	-0.76	-0.61
	16	-0.44	-0.43	-0.28	-0.97	-0.56	-0.85
	MEANODD	-0.69	-0.94	-0.52	-0.92	-0.28	-0.19
	MEANEVN	-0.58	-0.55	-0.33	-0.85	-0.13	-0.24
	MEANALL	-0.64	-0.75	-0.42	-0.88	-0.20	-0.21
	MEANODD SD	0.09	0.13	0.10	0.25	0.27	0.27
	MEANEVN SD	0.13	0.16	0.09	0.32	0.24	0.31
	MEANALL SD	0.12	0.24	0.13	0.28	0.26	0.28

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TABLE 2

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
SACRAMENTO, CALIFORNIA      DECEMBER 31, 1982  
SUM (S(2,C)) OF NET IC STATES (101-100-001)**

		<u>TM 1</u>	<u>TM 2</u>	<u>TM 3</u>	<u>TM 4</u>	<u>TM 5</u>	<u>TM 7</u>
CHANNEL	1	0.09	-0.01	-0.09	-0.55	-0.22	-0.52
	2	-0.12	-0.05	-0.23	-0.16	-0.01	-0.45
	3	-0.19	-0.27	-0.18	-0.67	—	-0.18
	4	-0.07	-0.02	-0.14	-0.24	-0.26	0.00
	5	-0.05	-0.39	-0.22	-0.50	0.00	-0.04
	6	0.00	-0.34	-0.26	-0.68	0.08	-0.13
	7	0.01	-0.46	-0.25	-0.75	0.19	-0.06
	8	0.07	-0.23	-0.06	-0.40	0.22	-0.03
	9	0.02	-0.39	-0.10	-0.45	-0.01	-0.07
	10	0.08	-0.31	-0.24	-0.55	0.14	-0.09
	11	-0.12	-0.42	-0.11	-0.48	0.10	-0.10
	12	-0.00	-0.21	-0.34	-0.64	0.12	0.02
	13	0.04	-0.22	-0.25	-0.46	-0.02	-0.07
	14	-0.16	-0.58	-0.24	-0.94	0.14	-0.01
	15	0.03	-0.41	-0.27	-0.10	-0.22	-0.38
	16	-0.04	-0.29	-0.15	-0.75	-0.09	-0.48
MEANODD		-0.01	-0.32	-0.18	-0.50	-0.02	-0.18
MEANEVN		-0.03	-0.25	-0.21	-0.54	0.10	-0.14
MEANALL		-0.02	-0.29	-0.20	-0.52	0.04	-0.16
MEANODD SD		0.09	0.15	0.07	0.19	0.15	0.17
MEANEVN SD		0.08	0.17	0.08	0.26	0.11	0.20
MEANALL SD		0.09	0.16	0.07	0.22	0.14	0.18

TABLE 3

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
 SACRAMENTO, CALIFORNIA DECEMBER 31, 1982  
 SUM (S(3,C)) OF NET IC STATES (011-010-001)

CHANNEL		TM 1	TM 2	TM 3	TM 4	TM 5	TM 7
	1	0.29	0.14	-0.04	-0.35	-0.28	-0.42
	2	0.41	0.07	0.02	-0.26	-0.14	-0.40
	3	0.32	-0.11	-0.16	-0.23	—	-0.23
	4	0.34	0.04	0.18	-0.07	0.08	-0.09
	5	0.28	-0.16	-0.15	-0.26	0.04	-0.10
	6	0.44	-0.08	-0.05	-0.18	-0.00	-0.21
	7	0.33	-0.34	-0.21	-0.88	-0.01	-0.10
	8	0.31	-0.24	0.16	-0.28	0.02	-0.17
	9	0.20	-0.20	-0.20	-0.40	-0.08	-0.19
	10	0.18	-0.35	-0.01	-0.51	0.00	-0.14
	11	0.06	-0.33	-0.17	-0.40	-0.03	-0.10
	12	0.30	-0.11	-0.08	-0.37	-0.06	-0.14
	13	0.32	-0.32	-0.10	-0.37	-0.10	-0.19
	14	0.10	-0.35	-0.03	-0.54	0.01	-0.12
	15	0.23	-0.24	-0.29	-0.24	-0.28	-0.46
	16	0.41	-0.19	0.27	-0.42	-0.21	-0.40
	MEANODD	0.25	-0.19	-0.17	-0.39	-0.11	-0.22
	MEANEVN	0.31	-0.15	0.06	-0.33	-0.03	-0.21
	MEANALL	0.28	-0.17	-0.05	-0.36	-0.07	-0.22
	MEANODD SD	0.09	0.16	0.07	0.20	0.12	0.14
	MEANEVN SD	0.11	0.16	0.13	0.16	0.09	0.12
	MEANALL SD	0.10	0.15	0.15	0.18	0.11	0.12

TABLE 4

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
 SACRAMENTO, CALIFORNIA DECEMBER 31, 1982  
 SUM (S(4,C)) OF NET IC STATES (111-100-010-001)

CHANNEL		TM 1	TM 2	TM 3	TM 4	TM 5	TM 7
	1	-0.197	-0.481	-0.713	-3.034	-1.035	-1.689
	2	-0.039	-0.297	-0.563	-1.594	-0.792	-1.643
	3	-0.439	-0.854	-0.806	-2.598	-	-0.445
	4	-0.106	-0.186	-0.071	-1.644	0.153	-0.360
	5	-0.385	-1.220	-0.716	-2.333	0.019	-0.361
	6	0.005	-0.962	-0.436	-2.397	-0.051	-0.463
	7	0.085	-1.409	-0.697	-3.466	0.169	-0.005
	8	0.027	-0.829	-0.054	-1.469	0.108	-0.512
	9	-0.226	-1.068	-0.666	-1.972	-0.011	-0.345
	10	-0.156	-0.967	-0.379	-3.898	0.160	-0.468
	11	0.054	-1.420	-0.606	-2.117	-0.020	-0.409
	12	-0.144	-0.696	-0.665	-2.135	0.037	-0.554
	13	-0.100	-0.869	-0.631	-2.624	-0.206	-0.495
	14	-0.377	-1.087	-0.549	-2.586	0.018	-0.490
	15	-0.095	-1.392	-0.751	-0.836	-1.022	-1.522
	16	-0.010	-0.796	-0.311	-2.264	-1.008	-1.907
	MEANODD	-0.163	-1.089	-0.698	-2.373	-0.301	-0.659
	MEANEVN	-0.100	-0.727	-0.378	-2.248	-0.159	-0.800
	MEANALL	-0.132	-0.908	-0.538	-2.310	-0.225	-0.729
	MEANODD SD	0.188	0.337	0.065	0.787	0.509	0.604
	MEANEVN SD	0.131	0.324	0.225	0.781	0.464	0.609
	MEANALL SD	0.160	0.370	0.230	0.760	0.473	0.590

TABLE 5

## POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4

COMPARISON OF AMBIENT AND VACUUM PULSE VALUES FOR SINGLE LAMP STATES  
(DIGITAL COUNTS)

BAND <sup>a</sup>	LAMP 100			LAMP 010			LAMP 001		
	VAC <sup>b</sup>	VAC <sup>c</sup>	AMB <sup>d</sup>	VAC <sup>b</sup>	VAC <sup>c</sup>	AMB <sup>d</sup>	VAC <sup>b</sup>	VAC <sup>c</sup>	AMB <sup>d</sup>
1O	106.69	106.67	107.95	68.54	68.47	70.45	46.32	46.22	48.52
1E	105.39	105.25	105.25	65.20	65.08	66.14	44.47	44.32	45.90
2O	99.45	99.15	100.56	78.75	78.40	79.45	45.40	45.23	47.40
2E	93.27	93.02	91.29	66.98	66.71	65.27	41.10	40.95	41.34
3O	94.36	94.01	89.95	69.07	68.76	67.21	40.13	39.95	39.91
3E	96.11	95.75	91.94	71.85	71.52	70.87	42.58	42.38	42.48
4O	96.01	95.89	91.61	98.92	98.66	95.43	47.00	46.94	46.74
4E	102.69	102.53	97.93	95.05	94.85	88.64	51.63	51.58	50.37
5O	44.96	44.87	46.23	41.30	41.19	42.70	24.23	24.14	25.01
5E	64.65	64.59	67.30	57.57	57.49	59.74	32.83	32.74	34.39
7O	57.19	57.10	59.21	45.08	44.95	47.24	32.34	32.27	33.75
7E	58.20	58.18	57.44	55.24	55.22	56.18	34.93	34.87	35.62

## NOTES:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.<sup>b</sup>VACUUM, MARCH 9, 1982, 12:43 P.M.<sup>c</sup>VACUUM, MARCH 9, 1982, 12:46 P.M.<sup>d</sup>AMBIENT, APRIL 27, 1982, 1:33 P.M.

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TABLE 6

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
AMBIENT GAIN CHANGES (ppt) RELATIVE TO MARCH 9, 1982, VACUUM**

BAND <sup>a</sup>	DATE			
	JANUARY 13 <sup>b</sup>	FEBRUARY 26 <sup>b</sup>	MARCH 12 <sup>c</sup>	MARCH 23 <sup>b</sup>
1O	28.63	31.38	21.62	30.88
1E	15.75	17.25	8.00	16.63
2O	25.12	26.25	19.75	24.38
2E	-9.40	-4.20	-13.90	-10.90
3O	-23.50	-23.50	-50.00	-18.25
3E	-18.63	-18.63	-46.25	-15.00
4O	-15.00	-15.00	-30.75	-10.13
4E	-27.38	-27.38	-47.00	-27.00

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

<sup>b</sup>CAL SHUTTER FLAG TEMPERATURE, 10.11 C°.

<sup>c</sup>CAL SHUTTER FLAG TEMPERATURE, 22.85 C°, SAME AS VACUUM RUN ON MARCH 9, 1982.

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conditions. The exact causes of the differences between ambient and vacuum measurements are not well understood, but are thought to be related to changes in optical surfaces or the filters caused by the deposit of thin water vapor films in ambient conditions.

After final prelaunch adjustments to the TM, several tests were conducted under vacuum conditions in early March to estimate instrument precision. The results (Table 7) indicate that variability in gain for repeated measurements over a timespan of a few days is generally less than 1 percent, but can occasionally be as high as 2 percent.

#### POSTLAUNCH SENSOR PERFORMANCE

A comparison of within-band relative gain changes yields a measure of TM precision that is somewhat insensitive to changes in the IC system. Table 8 shows the means and standard deviations of in-orbit gain changes in parts per thousand (ppt) relative to the 12:46 p.m. prelaunch vacuum test on March 9, 1982, for five dates ranging from August to December 1982. In the primary focal plane, channels in a band are internally consistent in gain change, varying up to only 0.6 percent (except for the 1-percent spread between even- and odd-numbered channels in band 2). In contrast, the cold focal plane channels demonstrate large within-band variability, up to 5 percent in band 5 and up to 3 percent in band 7 (excluding channel 7, which differs from the other channels in the band by up to 20 percent). Tables A-11 through A-13 in the appendix show the gain changes for each channel in bands 2, 5, and 7 relative to March 9. When a postlaunch data set (Washington, D.C., November 2, 1982) is used as a reference, within-band variability of gain change in the cold focal plane is substantially reduced. Table 9 shows that within-band gain changes relative to November 2 vary only up to 1.5 percent in band 5 and up to 0.7 percent in band 7 (channel 7 included). The divergence between even- and odd-numbered channels in band 2 has decreased to 0.5 percent. The reason for the inconsistency between prelaunch and postlaunch gain changes is unclear, but there are two possible causes: (1) the cold focal plane temperature during prelaunch is different from the in-orbit temperature and (2) the apparent postlaunch shift of the cold focal plane location, as indicated by band-to-band geometric registration studies, affects the shape of the IC calibration pulse.

The below-average performance of four channels needs to be singled out. Channel 3 in band 5 is dead, and channel 4 in band 2 has a very poor modulation transfer function. In the image product, data from both of these channels is replaced

TABLE 7

## PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4

CHANGE IN GAIN (ppt) RELATIVE TO MARCH 9, 1982, 12:46 P.M. PRELAUNCH VACUUM

DATE TIME TEMP <sup>c</sup> BAND <sup>a</sup>	FEB. 23 <sup>c</sup> 19:57 10.10	FEB. 24 <sup>c</sup> 10:09 22.85	MAR. 6 21:54 10.10	MAR. 7 2:55 22.85	MAR. 7 9:50 22.85	MAR. 9 7:25 22.85	MAR. 9 12:41 22.85	MAR. 9 12:50 10.10	MAR. 9 12:55 10.10	MAR. 9 20:21 22.85
10	-6	-28	-8	-6	-5	-11	7	-4	-8	-7
1E	-3	-27	-12	-11	-9	-12	7	-4	-8	-10
20	-8	-27	-3	-3	-1	-10	8	-3	-6	-5
2E	9	-15	-14	-13	-10	-12	8	-3	-7	-10
30	34	15	-12	-10	-8	-15	10	-4	-8	-10
3E	27	5	-10	-9	-7	-15	9	-4	-9	-9
40	48	38	-2	-1	-1	-2	5	0	-1	-1
4E	59	47	-4	-4	-4	-3	5	-1	-2	-2
50				-21	-16	-5	5	-1	-2	0
5E				-18	-14	-5	4	-1	-2	1
70				13	10	-1	3	0	-1	1
7E				12	10	-1	2	-1	0	1

## NOTES:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.<sup>b</sup>CAL SHUTTER FLAG TEMPERATURE.<sup>c</sup>EARLY VACUUM CHAMBER TESTING WITH UNSTABILIZED PROTOFLIGHT INSTRUMENT.

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TABLE 8

**POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
CHANGE IN GAIN (ppt) RELATIVE TO MARCH 9, 1982**

BAND	1982 DATE (DAY OF YEAR)				
	AUGUST 22 (234)	SEPTEMBER 10 (253)	OCTOBER 24 (297)	NOVEMBER 24 (320)	DECEMBER 8 (342)
1 MEAN	-35.2	-40.6	-52.0	-52.6	-51.6
SD	2.5	2.4	2.5	2.0	1.8
2 MEAN	-26.6	-30.3	-36.0	-34.1	-34.6
SD	7.7	7.3	6.3	6.3	6.3
3 MEAN	-27.8	-35.7	-48.0	-47.5	-49.3
SD	1.2	0.9	1.4	1.0	0.5
4 MEAN	-8.6	-14.6	-25.0	-27.3	-28.7
SD	1.6	1.1	1.8	1.4	1.4
5 MEAN	3.7	73.3	26.0	29.3	1.66
SD	10.4	11.4	10.2	10.2	10.8
7 MEAN	18.9	-2.6	34.0	-0.5	7.9
SD	45.2	45.6	46.1	43.8	44.4

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TABLE 9

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
CHANGE IN GAIN (ppt) RELATIVE TO D.C., NOVEMBER 2, 1982**

BAND	1982 DATE (DAY OF YEAR)				
	AUGUST 22 (234)	SEPTEMBER 10 (253)	OCTOBER 24 (297)	NOVEMBER 24 (328)	DECEMBER 8 (342)
1 MEAN	16.5	11.1	-1.5	-0.8	0.3
SD	1.5	2.1	1.5	1.3	0.8
2 MEAN	9.6	6.0	-0.4	2.0	1.7
SD	2.1	1.3	1.7	1.4	0.6
3 MEAN	21.5	13.4	0.6	2.1	0.1
SD	0.8	1.9	1.1	0.8	0.7
4 MEAN	16.6	10.7	-0.2	-2.1	-3.1
SD	1.0	0.9	0.8	0.8	0.8
5 MEAN	51.6	14.9	32.1	-29.5	-55.7
SD	3.6	3.5	1.5	8.6	5.1
7 MEAN	-6.2	-28.7	8.4	-25.6	19.6
SD	0.8	1.8	1.5	2.0	1.9

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with data from a neighboring channel (channel 4 in band 5 and channel 5 in band 2). Channel 2 in band 2 and channel 7 in band 7 are twice as noisy as the other channels in their respective bands; however, data collected from these channels are not replaced.

#### STABILITY WITH TIME

Study of the in-orbit gain changes with time characterizes the combined radiometric stability of the channels and the IC system. Table 10 lists the 26 scenes from which in-orbit gain data were collected. Figure 1 shows the location of these scenes. Figures 2 and 3 show gain change relative to prelaunch versus time for the six reflective bands. Figures A-1 through A-6 in the appendix show gain versus time for these bands. From launch through October 1982, gain decreased in the primary focal planes (6 percent in bands 1 and 2, 8 percent in band 3, and 3 percent in band 4), and then stabilized. In the cold focal plane bands, gain oscillates with time (up to 7 percent in band 5, and 5 percent in band 7). If the IC system itself were changing, an apparent decrease in gain in the cold focal plane channels as well as the primary focal plane channels should be observed. This is not the case, however, especially in band 7. The oscillation in bands 5 and 7 is difficult to explain since the oscillation periods of the two bands are not the same (55 days for band 5, and 75 days for band 7). Possible explanations such as temperature effects (arising from orbit precessions) on channel sensitivity or even relative position of the cold focal plane are apparently ruled out by the difference in frequency.

Although gain changes over a period of days are significant, the gain changes in all the reflective channels for successive rows of the same path are 1 ppt or less, except for band 1, channels 7, 10, and 11 (2 ppt); band 1, channel 12 (3 ppt); band 1, channel 4 (4 ppt); and band 4, channel 14 (2 ppt). Table 11 gives the differences between gains from the Kingston and Ottawa scenes. In all cases, the gain changes for scenes from successive rows in the same path are statistically insignificant (see percentage coefficients of variance, Table 12).

#### NOISE

To ensure positive detector readings at all times, the on-board electronics strives to maintain a constant background of about 2 counts. Table 13 and Tables A-14 and A-15 in the appendix give typical standard deviations in the background for each channel. The magnitude of background noise depends

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TABLE 10

# LANDSAT-4 TM SCENE IDENTIFICATION

ACQUISITION DATE	SCENE ID	WRS PATH/ROW	AREA
20 JUL 82	40004-15401	020/031	DETROIT, MICHIGAN
29 JUL 82	40011-31525	015/033	WASHINGTON, D.C.
7 AUG 82	40022-15061	014/032	NEW YORK/PHILADELPHIA
17 AUG 82	40032-15425	020/031	TOLEDO, OHIO
22 AUG 82	40037-16031	023/035	NORTHEAST ARKANSAS
25 AUG 82	40040-16321	028/030	FT. DODGE, IOWA
30 AUG 82	40045-15151	015/028	ATLANTIC OCEAN
10 SEP 82	40056-14541	012/031	BOSTON, MASSACHUSETTS
24 SEP 82	40070-16442	030/028	FORMAN, NORTH DAKOTA
26 SEP 82	40072-16325	028/030	NORTHWEST IOWA
27 SEP 82	40073-15400	019/037	ATLANTA, GEORGIA
24 OCT 82	40100-15182	016/028	OTTAWA, CANADA
24 OCT 82	40100-15184	016/029	KINGSTON, CANADA
2 NOV 82	40109-15140	015/033	WASHINGTON, D.C.
9 NOV 82	40116-18350	048/025	VANCOUVER, BRITISH COLUMBIA
17 NOV 82	40124-17495	040/035	DEATH VALLEY, CALIFORNIA
24 NOV 82	40131-17533	041/028	MT. HAMILTON, MONTANA
8 DEC 82	40145-18082	043/034	MODESTO, CALIFORNIA
20 DEC 82	40157-15174	015/041	FT. PIERCE, FLORIDA
22 DEC 82	40159-15032	013/036	CAPE HATTERAS, NORTH CAROLINA
31 DEC 82	40168-18141	044/033	SACRAMENTO, CALIFORNIA
3 JAN 83	40171-	033/037	WHITE SANDS, NEW MEXICO
3 JAN 83	40171-	033/038	WHITE SANDS, NEW MEXICO
6 JAN 83	40174-17372	038/033	MARYSVILLE, UTAH
15 JAN 83	40183-17332	037/038	LUKEVILLE, ARIZONA
29 JAN 83	40197-02267	112/211	WEST WASHINGTON, D.C., PM

000010471 00

FIGURE 1

# The U.S. With WRS Path/Row Scenes Indicated

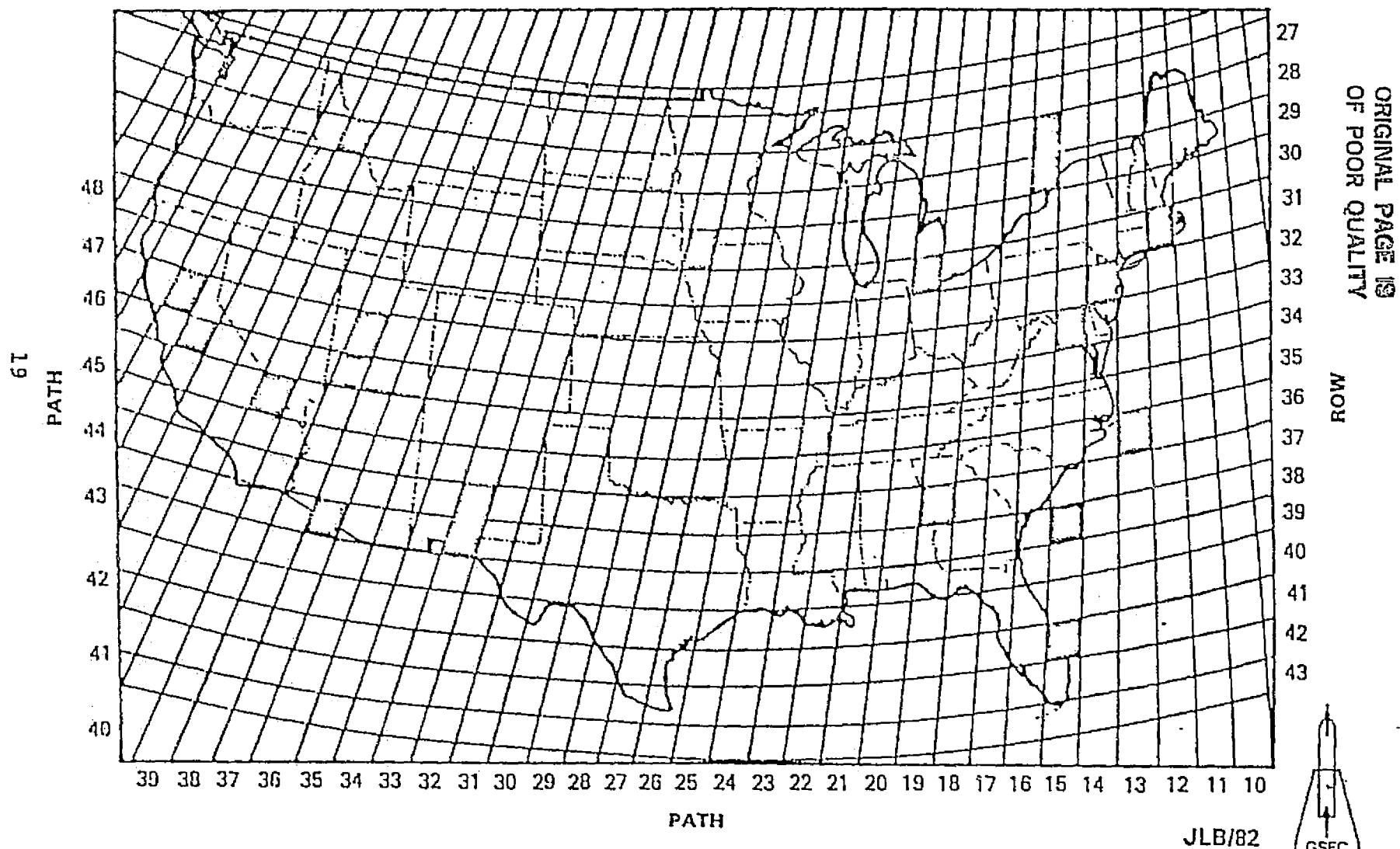
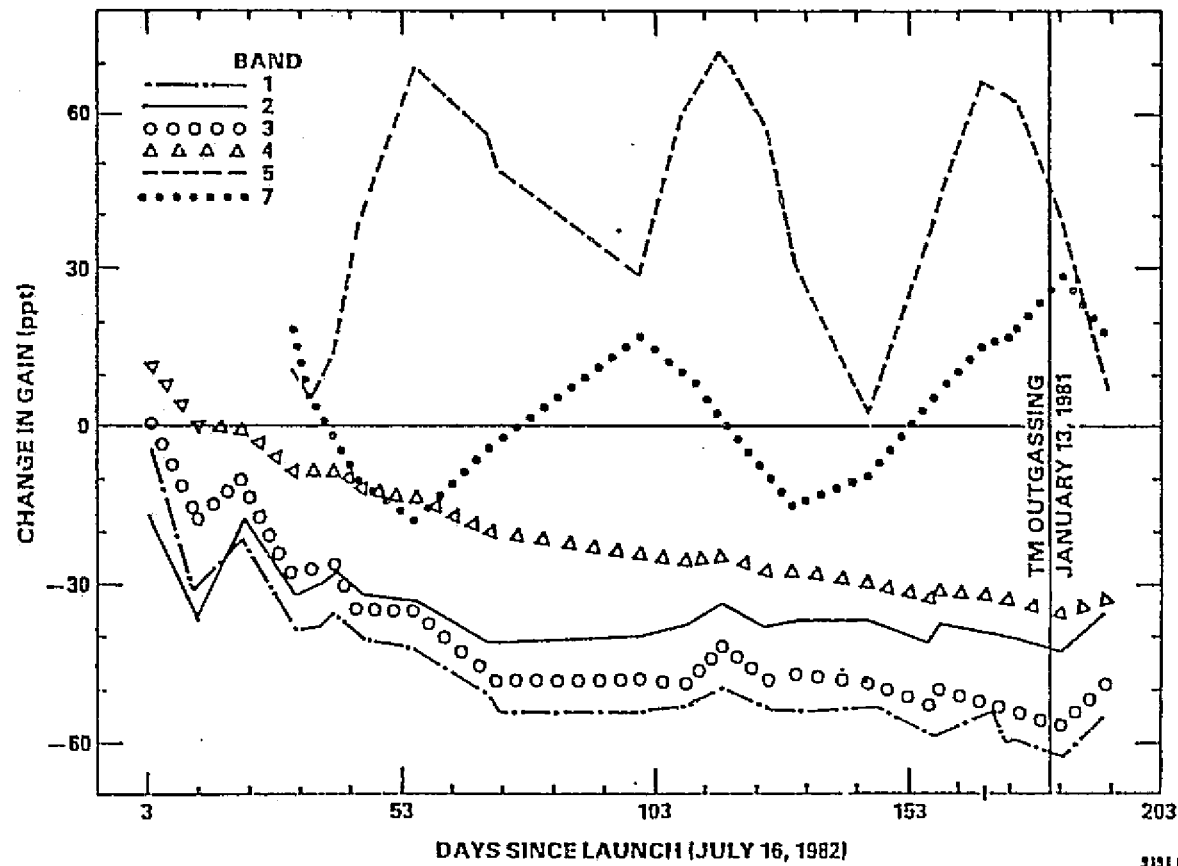


FIGURE 2

POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
CHANGE IN GAIN (ppt) EVEN DETECTORS RELATIVE TO MARCH 9, 1982

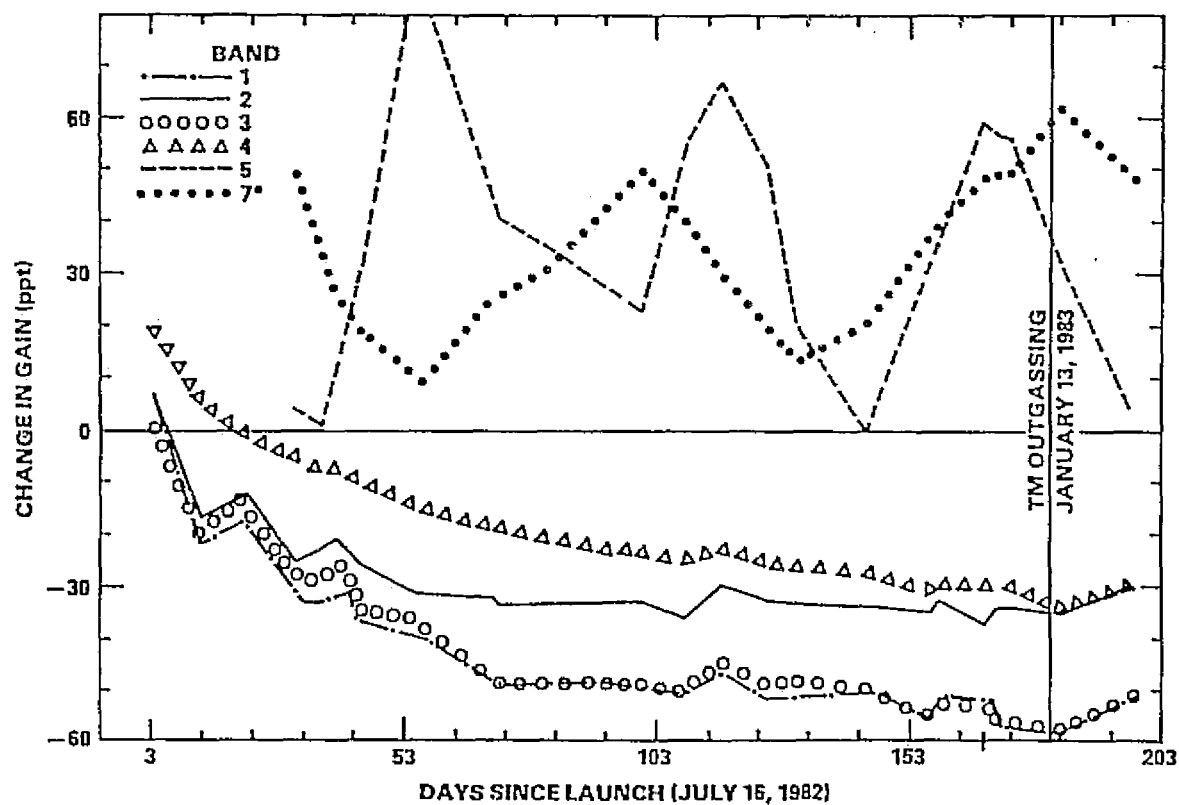


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FIGURE 3

POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
CHANGE IN GAIN (ppt) ODD DETECTORS RELATIVE TO MARCH 9, 1982



\*INCLUDES BAND 7, CHANNEL 7

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TABLE 11

# STABILITY OF THE IC WITH TIME

GAIN DIFFERENCES BETWEEN KINGSTON (40100—15184) AND  
OTTAWA (40100—15182) IN COUNTS/MW  $\text{cm}^{-2} \text{sr}^{-2} \mu\text{m}^{-1}$

CHANNEL	TM1	TM2	TM3	TM4	TM5	TM7
1	0.017	0.005	0.010	0.014	-0.033	0.105
2	0.000	-0.004	0.000	0.006	0.021	0.067
3	0.005	-0.002	0.006	-0.001	—	0.149
4	0.059	0.000	0.000	0.001	0.097	0.120
5	0.003	0.005	-0.005	0.000	0.015	0.077
6	0.009	0.008	0.006	0.006	-0.019	-0.053
7	0.025	-0.001	0.010	0.013	0.093	0.070
8	0.020	-0.002	-0.007	-0.007	0.002	0.104
9	-0.005	0.005	0.002	0.010	-0.014	-0.066
10	0.037	0.008	0.006	0.003	-0.008	0.133
11	0.024	0.000	0.001	-0.001	-0.038	0.002
12	0.049	-0.003	0.003	0.013	0.057	0.063
13	0.009	0.002	0.003	-0.012	0.012	0.038
14	-0.002	0.001	0.001	0.019	0.007	0.019
15	0.020	0.000	0.011	0.015	-0.102	-0.014
16	0.003	-0.004	0.004	-0.001	0.009	0.189
MEANODD	0.012	0.002	0.006	0.005	-0.013	-0.046
MEANEVEN	0.022	0.000	0.002	0.004	0.020	0.093
MEAN	0.018	0.001	0.004	0.005	0.005	0.077

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TABLE 12

STABILITY OF THE IC WITH TIME

PERCENTAGE COEFFICIENT OF VARIANCE OF GAIN  
KINGSTON, CANADA (40100-15184)

		TM1	TM2	TM3	TM4	TM5	TM7
CHANNEL	1	0.477	0.614	0.535	0.772	0.265	0.472
	2	0.513	0.521	0.530	1.197	0.352	0.463
	3	0.456	0.647	0.497	0.722	—	0.512
	4	0.524	0.488	0.574	1.247	0.321	0.443
	5	0.473	0.675	0.545	0.778	0.230	0.450
	6	0.549	0.549	0.573	1.171	0.342	0.426
	7	0.525	0.661	0.516	0.823	0.262	0.498
	8	0.494	0.522	0.553	1.167	0.336	0.435
	9	0.499	0.701	0.557	0.874	0.286	0.474
	10	0.462	0.544	0.568	1.213	0.355	0.448
	11	0.548	0.631	0.539	0.797	0.225	0.506
	12	0.531	0.471	0.531	1.233	0.352	0.429
	13	0.532	0.698	0.518	0.770	0.250	0.463
	14	0.474	0.521	0.551	1.157	0.407	0.432
	15	0.506	0.640	0.542	0.803	0.309	0.465
	16	0.483	0.511	0.572	1.205	0.360	0.451
	MEANODD	0.502	0.658	0.531	0.792	0.261	0.480
	MEANENVN	0.504	0.516	0.557	1.199	0.353	0.441
	MEANALL	0.503	0.587	0.544	0.996	0.310	0.460

$$CV = \frac{N \cdot 100}{\sum X_i} \sqrt{\frac{(N/N-2) \cdot \sum (Y_i - GX_i - B)^2}{N \sum X_i^2 - (\sum X_i)^2}}$$

WHERE CV = PERCENT COEFFICIENT OF VARIANCE

N = NUMBER OF MEASUREMENTS

Y<sub>i</sub> = DIGITAL COUNTS

G = GAIN (DIGITAL COUNT/RADIANCE)

X<sub>i</sub> = RADIANCE (MW cm<sup>-2</sup> sr<sup>-1</sup> μm<sup>-1</sup>)

B = OFFSET IN DIGITAL COUNTS

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TABLE 13

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STANDARD DEVIATION OF WATER IMAGE, BOSTON,  
SEPTEMBER 10, 1982 (DIGITAL COUNTS)

CHANNEL		TM1	TM2	TM3	TM4	TM5	TM7
	1	1.51	0.67	0.96	0.38	0.86	1.02
	2	1.77	1.06	0.85	0.48	0.82	1.04
	3	1.46	0.57	0.83	0.35	—	0.93
	4	1.77	0.80	1.06	0.52	0.90	1.07
	5	1.42	0.58	0.86	0.49	0.97	0.99
	6	1.76	0.62	0.82	0.36	0.94	1.05
	7	1.58	0.52	0.84	0.49	1.21	1.91
	8	1.67	0.48	1.15	0.56	0.86	0.94
	9	1.46	0.56	0.77	0.45	0.83	1.09
	10	1.49	0.55	0.86	0.38	0.86	1.12
	11	1.59	0.54	0.71	0.49	0.89	1.06
	12	1.60	0.53	0.78	0.50	0.82	1.09
	13	1.48	0.61	0.86	0.50	0.84	0.98
	14	1.68	0.57	0.87	0.42	0.76	1.15
	15	1.56	0.61	0.87	0.51	0.81	0.97
	16	1.95	0.59	1.11	0.43	0.73	1.00
	MEANODD	1.51	0.58	0.84	0.46	0.92	1.12
	MEANENV	1.71	0.65	0.94	0.46	0.84	1.06
	MEANALL	1.61	0.62	0.89	0.46	0.87	1.09
	MEANODD SD	0.06	0.04	0.07	0.06	0.13	0.32
	MEANENV SD	0.13	0.18	0.14	0.07	0.06	0.06
	MEANALL SD	0.14	0.13	0.12	0.06	0.11	0.22
	MEANALL CV	9.11	22.13	13.67	13.68	12.67	20.74

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primarily on the band and secondarily on whether the detector is in the even or the odd bank. Band 1 is noisiest at 1.2 counts, followed by band 7. Bands 2 and 4 are quietest, with noise of up to 0.5 count. In the primary focal plane, the even-numbered detectors are 0.1 to 0.2 count noisier than the odd-numbered detectors. In the cold focal plane, the odd-numbered detectors are slightly (less than 0.1 count) noisier than the even-numbered detectors. Noise in the image is of comparable magnitude to background noise and follows the same pattern, indicating that noise in the image arises primarily from noise in the background. Table 14 gives the standard deviation by channel of the image with a flooding lamp target. The image area is 24 midscan pixels by 400 scans. An estimate of the upper limit of postlaunch noise in the image was obtained by examining a water scene in Boston harbor (September 10, 1982). The image area was 512 pixels by 32 scans (512 lines). Table 15 gives the standard deviation of the signal for each channel. The results are consistent with the prelaunch pattern.

The only significant coherent noise peaks appear at 32.7 kilohertz (kHz). Table 16 gives the peak-to-peak amplitudes (background subtracted) at 32.7 kHz derived from fast Fourier transforms of the first scan (1024 samples per detector) of video data in the August 22, 1982, Memphis scene. It should be noted that the largest amplitude occurs in band 1, channel 16, and is 1.43 counts. The first scan of background data from the August 22, 1982, Missouri scene showed a similar peak-to-peak amplitude of 1.58 counts in band 1, channel 16, at 32.7 kHz. Both of these data sets were collected while the Multispectral Scanner (MSS) was turned on. In contrast, the scene of White Sands, New Mexico, on January 3, 1983, which was collected when the MSS was turned off, showed no coherent noise. Table 17 shows the coherent noise pattern from the first reverse scan of prelaunch, March 9, 1982, flooding lamp image data (52 samples per detector). In general, the pattern is similar to postlaunch data, although the amplitudes are somewhat smaller.

#### OTHER FACTORS AFFECTING DATA QUALITY

##### Location of Calibration Collect Window

The Scrounge ground system hardware can only extract 200 minor frames of the 1115 minor frames generated during scan minor turnaround. Fifty-two minor frames are selected from the background region; the remaining 148 minor frames contain calibration pulse data. The location of the 148-frame window is fixed relative to line start and depends

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TABLE 14

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STANDARD DEVIATION OF FLOODING LAMP IMAGE,  
MARCH 9, 1982 (DIGITAL COUNTS)

		TM1	TM2	TM3	TM4	TM5	TM7
CHANNEL	1	1.53	0.65	0.82	0.52	1.28	1.33
	2	1.73	1.06	0.81	0.49	1.11	1.30
	3	1.44	0.57	0.85	0.55	—	1.42
	4	1.21	0.63	0.90	0.58	1.04	1.33
	5	1.39	0.62	0.86	0.44	1.09	1.31
	6	1.63	0.64	0.83	0.50	1.45	1.45
	7	1.32	0.56	0.76	0.51	1.32	3.82
	8	1.53	0.57	1.23	0.62	1.10	1.40
	9	1.35	0.57	0.90	0.37	1.04	1.35
	10	1.18	0.57	1.03	0.65	1.41	1.59
	11	1.56	0.56	1.03	0.39	1.16	1.45
	12	1.17	0.60	0.95	0.46	1.12	1.27
	13	1.41	0.52	0.80	0.57	1.09	1.31
	14	1.53	0.58	1.01	0.49	1.10	1.39
	15	1.53	0.75	0.81	0.49	1.33	1.32
	16	1.94	0.79	0.81	0.43	1.12	1.43
MEANODD		1.44	0.60	0.85	0.48	1.19	1.66
MEANENVN		1.49	0.68	0.95	0.53	1.18	1.40
MEANALL		1.47	0.64	0.90	0.50	1.18	1.53
MEANODD SD		0.08	0.07	0.08	0.07	0.12	0.87
MEANENVN SD		0.28	0.16	0.14	0.08	0.15	0.10
MEANALL SD		0.20	0.13	0.12	0.07	0.13	0.61
MEANALL CV		13.85	20.42	13.61	15.38	11.43	40.21

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TABLE 15

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STANDARD DEVIATION OF BACKGROUND, BOSTON,  
SEPTEMBER 10, 1982 (DIGITAL COUNTS)

CHANNEL		TM1	TM2	TM3	TM4	TM5	TM7
	1	1.21	0.47	0.74	0.58	0.80	0.99
	2	1.36	1.00	0.56	0.52	0.75	0.99
	3	1.11	0.48	0.55	0.59	—	0.85
	4	1.40	0.70	0.70	0.52	0.81	1.03
	5	1.03	0.43	0.52	0.51	0.87	0.92
	6	1.34	0.52	0.53	0.58	0.87	1.00
	7	1.21	0.37	0.48	0.47	1.07	1.96
	8	1.24	0.43	0.86	0.69	0.82	0.92
	9	1.01	0.30	0.42	0.48	0.82	0.95
	10	1.11	0.30	0.57	0.32	0.87	1.03
	11	1.14	0.35	0.36	0.44	0.89	0.91
	12	1.30	0.37	0.51	0.63	0.84	1.00
	13	1.05	0.37	0.52	0.39	0.82	0.81
	14	1.30	0.38	0.61	0.54	0.79	1.08
	15	1.16	0.34	0.52	0.48	0.80	0.79
	16	1.56	0.45	0.87	0.56	0.77	0.96
	MEANODD	1.11	0.39	0.51	0.49	0.87	1.02
	MEANEVN	1.33	0.52	0.65	0.57	0.81	1.00
	MEANALL	1.22	0.45	0.58	0.53	0.84	1.01
	MEANODD SD	0.08	0.06	0.11	0.06	0.09	0.38
	MEANEVN SD	0.12	0.22	0.14	0.06	0.04	0.04
	MEANALL SD	0.15	0.17	0.14	0.07	0.07	0.26
	MEANALL CV	12.27	38.37	24.35	13.76	8.87	25.98

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TABLE 16  
**IN-ORBIT LANDSAT-4 TM RADIOMETRIC COHERENT NOISE  
 (DIGITAL COUNTS)**

Channel No.	Peak-to-Peak Coherent Noise at 32 KHz (DN)					
	Band 1	Band 2	Band 3	Band 4	Band 5	Band 7
1	.54	.08	.09	.28	.25	.16
2	.98	.13	.13	.39	.50	.28
3	.74	.07	.07	.42	—	.20
4	.03	.15	.86	.77	.19	.37
5	.83	.15	.20	.76	.33	.35
6	1.02	.16	.19	.49	.25	.21
7	.39	.10	.15	.58	.59	.46
8	.93	.00	.80	.70	.34	.29
9	.44	.08	.16	.43	.38	.25
10	.33	.14	.08	.35	.19	.28
11	.54	.13	.17	.37	.29	.18
12	.47	.13	.10	.35	.41	.31
13	.52	.05	.21	.43	.20	.26
14	.76	.00	.12	.28	.25	.34
15	.57	.06	.09	.34	.32	.18
16	1.43	.06	.35	.37	.49	.20

Data Measured Peak-to-Peak, With Background Subtracted in Digital Counts  
 Data from Scene W023036 ID = 40037-16033 (22 Aug 82) Memphis, TN

TABLE 17

# **PRELAUNCH LANDSAT-4 TM COHERENT NOISE (DIGITAL COUNTS)**

CHANNEL NUMBER	PEAK-TO-PEAK COHERENT NOISE AT 32.7 KHz (COUNTS)					
	BAND 1	BAND 2	BAND 3	BAND 4	BAND 5	BAND 7
1	0.75					
2	0.69					
3	0.75					
4	—		0.23	0.22		
5	0.56		0.41		0.44	
6	1.06			0.31	0.50	
7	0.38					
8	0.72		0.63	0.47		
9	0.56					
10	0.69				0.44	
11	1.00					
12	0.25					
13	0.56			0.50		
14	0.50					
15	0.50				0.50	
16	1.00		0.53			

## **NOTES:**

DATA MEASURED PEAK TO PEAK WITH BACKGROUND SUBTRACTED IN DIGITAL COUNTS.

DATA FROM FIRST REVERSE SCAN OF FLOODING LAMP DATA (52 SAMPLES PER CHANNEL) MARCH 9, 1982.

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only on scan direction. The location of the pulse within the window depends on the channel number, the band number, and the line length (varies up to 10 minor frames), as well as on the scan direction. In the forward scan direction, the pulse leading-edge minor frame number increases for a given scan as the channel number decreases. Band number is considerably less important than channel number in determining pulse location. With TM protoflight band 1, channel 1 is the farthest to the right (starts at the highest minor frame number), followed by bands 2 and 3. Using the Hughes method, pulse width varies from 42 to 44 minor frames in the primary focal plane band and 40 to 41 frames in bands 5 and 7. A more detailed description of the scan timeline is given in Barker, Abrams, et al. (1984).

For scene data processed by the Scrounge system before December 22, 1982, the beginning of the 148-frame window was located at minor frame 7009 for forward scans and 6525 for reverse scans. The location of the forward scan calibration pulse window caused part of the calibration pulse to fall outside the window in channel 1 on all bands, and in channel 2 on bands 1, 2, and 3. Figure 4 shows a raw data dump of a truncated pulse. As a result of pulse truncation, gain was underestimated by 3.8 percent in channel 1 of band 1; 0.6 percent in channel 1 of band 2; 0.2 percent in channel 1 of band 5 and channel 2 of bands 1 and 2; and 0.1 percent in channel 1 of bands 3, 4, and 7 and channel 2 of band 3. On December 22, the calibration window was reset to begin at minor frame 7029 in the forward direction and minor frame 6517 in the reverse direction. This adjustment eliminated truncation, but it occasionally introduced a new problem. The new positions of the collect windows were such that data from the transition region (from full obscuration of the optical axis by the shutter to full imaging) were occasionally included in the collect window. This happened primarily for channels 16, 15, and 14 in both forward and reverse scans. Because the transition data had a higher count level than the lamps-off 000 IC state, "pulse" averages for the 000 state had an abnormally high digital count level. The offset values for channels 16, 15, and 14 resulting from the linear regression analysis also tended to be high (up to 18 digital counts). A compromise set of calibration windows that will eliminate this problem is currently being proposed. Table 18 gives the history of the calibration collect window location.

### Acquisition

Two scenes collected via the Prince Albert ground station have been examined in detail: Hamilton, Montana, on November 24, 1982, and Vancouver, British Columbia, on

FIGURE 4

# RAW DATA DUMP OF TRUNCATED PULSE

TRAPP PROGRAM      SCN ID/ PATHROW : 4010915140/ DCGFSC    RUN ON DATE: 12-APR-83 AT TIME: 12:34:29

PAGE NO. 17

SORTED AND SIGN CORRECTED CALIBRATION DATA, FORWARD DIRECTION, SCAN # 1, DET # 1

5	4	2	4	4	2	2	5	4	1	4	2	5	4	4	5	3	5	4	2	4	3	2	5	3	3	4	2	2	4	4	2
3	5	2	4	5	3	2	5	2	4	4	4	2	4	3	3	2	5	3	3	5	3	4	3	5	2	4	3	4	3	5	2
4	3	5	2	5	4	3	5	4	1	5	4	2	4	5	3	3	4	5	4	5	6	3	5	6	3	5	6	4	4	6	4
5	8	8	6	10	9	12	17	25	33	42	54	60	68	75	81	86	91	93	98	99	99	99	98	104	103	105	108	109	108	116	112

TABLE 18

# **IN-ORBIT 148-mf CALIBRATION COLLECT WINDOWS**

PERIOD	FORWARD SCAN (mf)	REVERSE SCAN (mf)
LAUNCH TO DECEMBER 22, 1982	7009	6525
DECEMBER 22, 1982, TO PRESENT	7029	6517
PROPOSED COMPROMISE	7017	6525
PROPOSED CENTERED	7037	6513

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November 9, 1982. Background noise (standard deviation) in the Vancouver scene was about 0.1 count larger in bands 1, 2, and 3 than is typical for scenes collected via the transportable ground station. The data from these two scenes were otherwise comparable to data collected via the transportable ground station.

#### Nonuniformity in the A/D Converter

The conversion from voltage to digital counts by the analog-to-digital (A/D) converter is linear, but the cutoff (threshold) voltages are not spaced uniformly (Barker, 1984). The voltage range allocated to a digital count level varies anywhere from 3 to 22 millivolts. The least two significant bits in the digital count value are closely correlated with the size of the allocated range. A higher digital count level still implies a higher radiance, but the precision of the radiance value depends on the count level of the raw data. Table A-16 in the appendix lists the threshold voltage and bin size for each count level for band 1, channel 1. The pattern for the other channels is similar but not identical.

As a result of the nonuniformity in the A/D converter, histograms of raw scene data are saw-toothed. When the raw histogram is normalized using the following equation, the resulting histogram is smoother:

$$C'(n) = \frac{C(n) \cdot \bar{b}}{b(n)}$$

where  $C(n)$  = number of pixels at digital level  $n$   
 $C'(n)$  = normalized count for digital level  $n$   
 $\bar{b}$  = average bin size in millivolts  
 $b(n)$  = bin size for level  $n$

Figure 5 shows the raw histogram collected by band 1, channel 1, on January 3, 1983, over White Sands, New Mexico. Figure 6 shows the same histogram after normalization to remove the effects of A/D nonuniformity.

#### POSSIBLE ADJUSTMENTS TO RADIOMETRIC CALIBRATION PROCEDURES

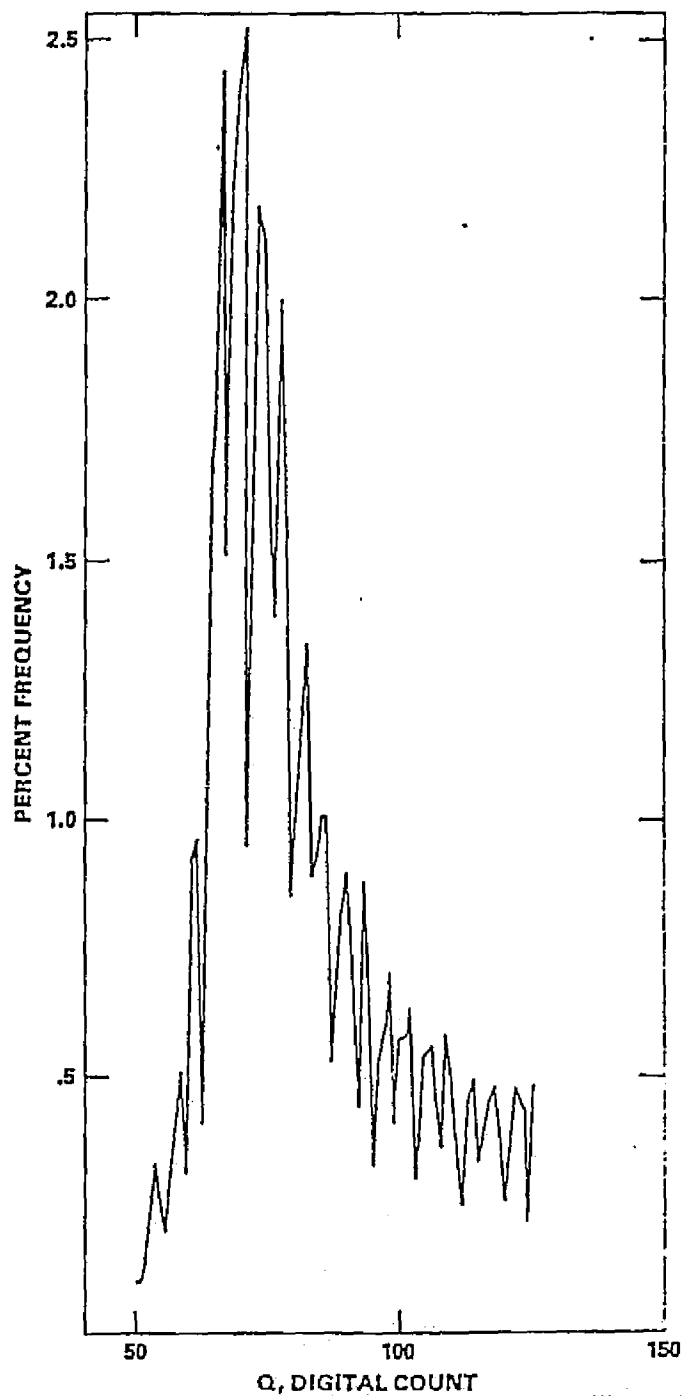
##### PULSE INTEGRATION.

The standard deviation of integrated pulse values is sensitive to pulse integration width. In general, the larger the integration width, the lower the variability in the integrated pulse value for a given channel and IC state. Figure 7 shows the change in standard deviation with pulse integration width for channel 9, IC state 110, in all bands. The rise in standard deviation when the integration width

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FIGURE 5

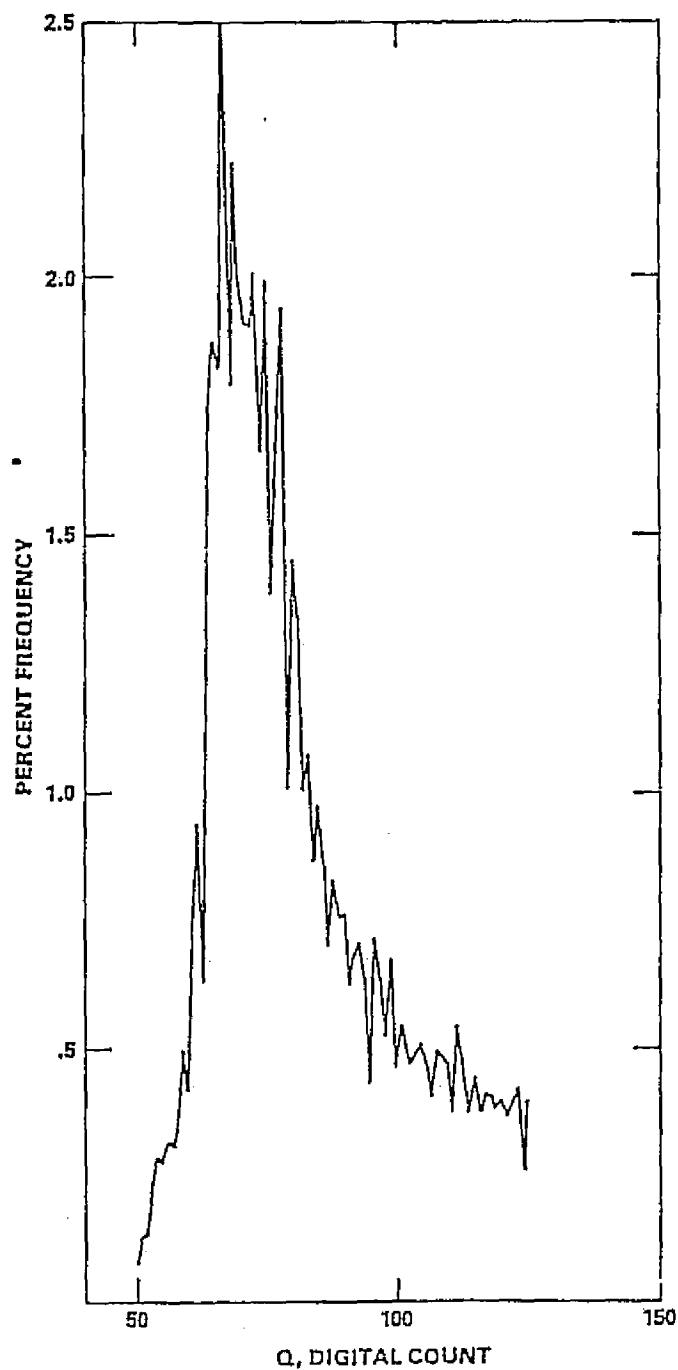
POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
HISTOGRAM TM1, CHANNEL 1, RAW DATA  
WHITE SANDS, NEW MEXICO, JANUARY 3, 1983



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FIGURE 6

POSTLAUNCH RADIOMETRIC CALIBRATION — LANDSAT-4  
HISTOGRAM TM1, CHANNEL 1, NORMALIZED  
WHITE SANDS, NEW MEXICO, JANUARY 3, 1983

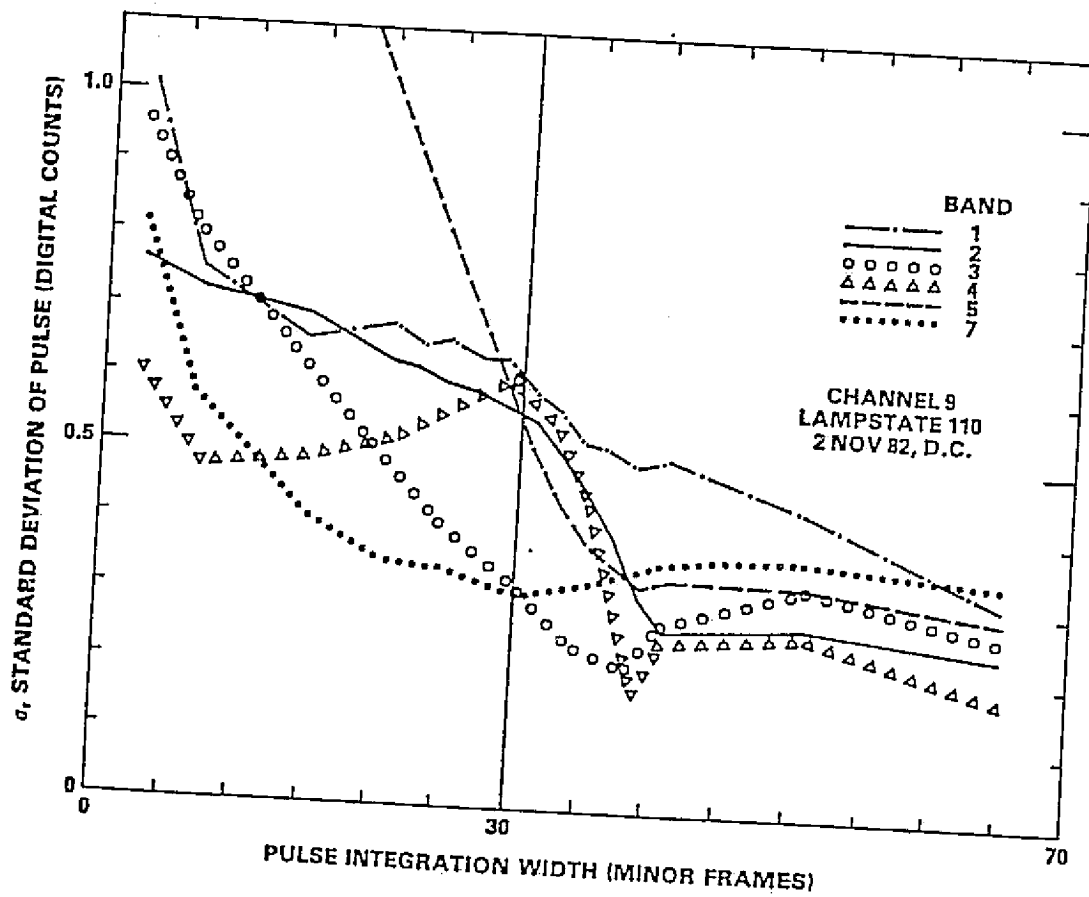


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FIGURE 7

LANDSAT-4 TM RADIOMETRIC PREPROCESSING  
PARAMETRIC STUDY OF PEAK INTEGRATION WIDTH



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cuts the pulse at the "shoulder" should be noted. As a result of line length variation ( $\pm 10$  minor frames) and a channel-dependent variation of pulse location of approximately 80 minor frames, pulse truncation cannot be safely avoided with a pulse integration width larger than 45. Integration widths that reduce standard deviation, avoid the pulse "shoulder," and avoid the risk of pulse truncation are given in Table 19. The two methods of locating the pulse center, the Hughes method used by the Scrounge system and the Thresh method, result in nearly identical pulse center locations (see Table 20, courtesy of Fred Alyea of GE). The critical variable is the integration width.

#### PULSE AVERAGING

The standard deviation of the pulse values is reduced when scans surrounding an IC state transition are eliminated from the pulse average. Tables 21 and 22 give the standard deviations when 2 to 20 scans are excluded from the average following the two types of transition, lamp turn-on and lamp turn-off. After lamp turn-on, there is an initial overshoot involving 1 to 3 scans, followed by a small undershoot involving 1 scan (Figures 8 and A-7 to A-17) before the count level stabilizes. Following lamp turn-off, the heat radiation from the still-hot lamp contributes to the radiance measured in the mid-infrared (IR) (cold focal plane) bands. The heat radiation persists at measurable levels for about 10 scans. Table 23 gives the standard deviations when up to six scans preceding a transition are eliminated from the average. It should be noted that improved results are obtained for cold focal plane channels (1) when four scans are excluded before the sensing of a condition indicating a lamp turn-off transition and (2) when two scans are excluded before the sensing of a lamp turn-on transition. No clear physical explanation for these empirical results is available. Table 24 gives the standard deviations at all eight IC levels obtained using the improved parameters and those obtained using the original parameters to analyze the scene from November 2, 1982, of Washington, D.C.

#### CALIBRATION

The authors tested a least-square regression analysis using a quadratic relationship between digital counts and radiance:

$$Q = a + bR + dR^2$$

TABLE 19

# **POSTLAUNCH RADIOMETRIC CALIBRATION TM LANDSAT-4**

## **IMPROVED PARAMETERS**

<b>BAND<sup>a</sup></b>	<b>PULSE WIDTH (MINOR FRAMES)</b>	<b>SCANS<sup>b</sup> AT END (MINOR FRAMES)</b>	<b>SCANS<sup>c</sup> AT BEGINNING (MINOR FRAMES)</b>
1O	39	2	4
1E	41	2	4
2O	41	2	4
2E	41	2	4
3O	37	2	4
3E	35	2	4
4O	39	2	4
4E	41	2	4
5O	39	4	10
5E	39	4	8
7O	33	4	14
7E	33	4	12

### **NOTES:**

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

<sup>b</sup>SCANS TO DROP FROM AVERAGE AT END OF PLATEAU, i.e., BEFORE A TRANSITION.

<sup>c</sup>SCANS TO DROP FROM AVERAGE AT BEGINNING OF PLATEAU, i.e., AFTER A TRANSITION

TABLE 20

**CENTER INDICES FOR FORWARD SCANS  
USING THRESH AND HUGHES ALGORITHMS<sup>a</sup>**

<b>THRESH (RELATIVE mf)</b>	<b>HUGHES (RELATIVE mf)</b>
115.000	115.500
116.000	116.500
116.000	116.500
115.000	115.500
116.000	116.500
115.500	116.000
115.000	115.500
115.500	116.000
116.000	116.500
116.000	116.500
116.000	116.500
116.500	117.000
117.000	117.000
116.500	116.500
116.500	116.500
116.000	116.500
115.000	116.500
116.000	116.500
116.500	117.000

<sup>a</sup>INFORMATION USED IN THIS TABLE WAS GENERATED BY FRED  
ALYEA AND ERIC BEYER OF GENERAL ELECTRIC COMPANY.

361-BA/AB-112\*)  
JLB/RBA 3/83

TABLE 21

# **POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4 STANDARD DEVIATION vs. NUMBER OF SCANS DROPPED AFTER A LAMP TURN-ON TRANSITION**

STATE 110, D.C., NOVEMBER 2, 1982

BAND <sup>a</sup>	SCAN									
	2	4	6	8	10	12	14	16	18	20
1O	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.54	0.51	0.52
1E	0.53	0.55	0.55	0.56	0.55	0.55	0.55	0.52	0.52	0.53
2O	0.28	0.28	0.28	0.28	0.27	0.27	0.27	0.27	0.27	0.26
2E	0.32	0.31	0.31	0.31	0.31	0.31	0.31	0.30	0.30	0.31
3O	0.42	0.41	0.41	0.41	0.39	0.40	0.39	0.40	0.40	0.42
3E	0.32	0.30	0.30	0.30	0.30	0.29	0.30	0.30	0.30	0.30
4O	1.14	1.13	1.12	1.12	1.12	1.11	1.09	1.12	1.12	1.13
4E	0.63	0.59	0.58	0.58	0.59	0.59	0.60	0.60	0.60	0.61
5O	0.58	0.35	0.28	0.27	0.27	0.26	0.26	0.27	0.27	0.27
5E	0.81	0.46	0.38	0.36	0.34	0.34	0.34	0.34	0.34	0.34
7O	1.04	0.66	0.51	0.47	0.47	0.44	0.45	0.46	0.46	0.45
7E	1.23	0.74	0.54	0.47	0.43	0.43	0.40	0.40	0.39	0.40

NOTE:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

361-BA/AD-113\*  
JLB/RDA 2/83

TABLE 22

# POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4 STANDARD DEVIATION vs. NUMBER OF SCANS DROPPED AFTER A LAMP TURN-OFF TRANSITION

STATE 110, D.C., NOVEMBER 2, 1982

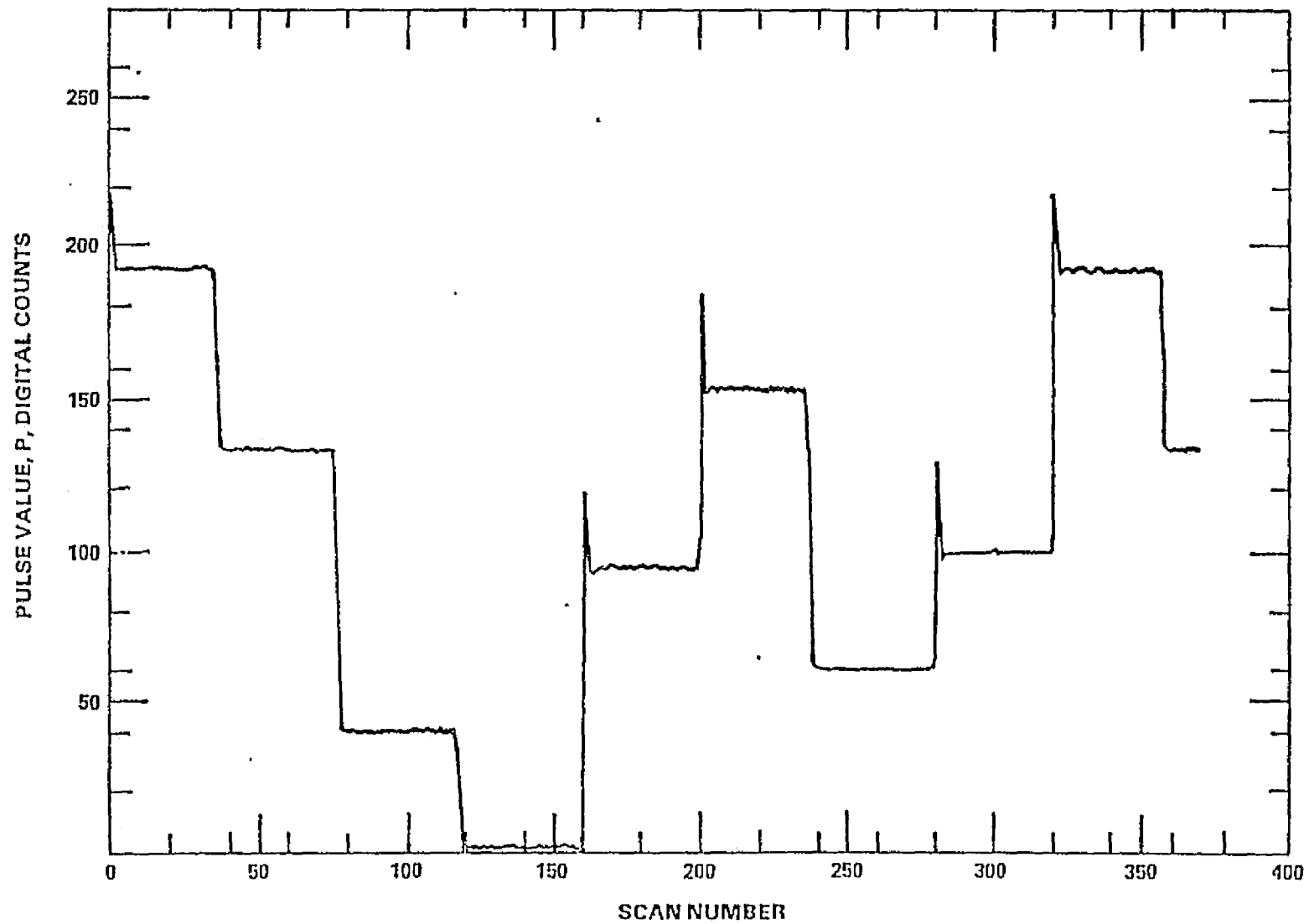
BAND <sup>a</sup>	SCAN									
	2	4	6	8	10	12	14	16	18	20
1O	0.57	0.57	0.57	0.58	0.59	0.60	0.60	0.61	0.61	0.62
1E	0.70	0.69	0.70	0.70	0.71	0.71	0.68	0.69	0.67	0.62
2O	0.83	0.63	0.63	0.63	0.62	0.63	0.64	0.63	0.61	0.61
2E	0.70	0.60	0.61	0.60	0.60	0.61	0.61	0.60	0.61	0.62
3O	0.45	0.34	0.34	0.34	0.35	0.34	0.32	0.32	0.33	0.30
3E	0.41	0.31	0.31	0.30	0.30	0.30	0.29	0.28	0.28	0.28
4O	1.26	1.28	1.29	1.29	1.14	1.15	1.15	1.14	1.15	1.15
4E	0.68	0.62	0.62	0.62	0.63	0.61	0.61	0.61	0.62	0.62
5O	0.43	0.42	0.42	0.43	0.43	0.44	0.45	0.46	0.45	0.44
5E	0.58	0.57	0.57	0.57	0.57	0.55	0.56	0.55	0.56	0.57
7O	0.49	0.49	0.50	0.49	0.49	0.50	0.50	0.49	0.50	0.50
7E	0.48	0.46	0.45	0.45	0.46	0.46	0.46	0.46	0.46	0.45

NOTE:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

FIGURE 8

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM1 CHANNEL 9 ID = 40109-15140 PULSE VALUES



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TABLE 23

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STANDARD DEVIATION vs. NUMBER OF SCANS DROPPED  
BEFORE A TRANSITION**

BAND <sup>a</sup>	SCAN							
	LAMP TURN-OFF, STATE 110, D.C., NOVEMBER 2, 1982				LAMP TURN-ON, STATE 011, D.C., NOVEMBER 2, 1982			
	0	2	4	6	0	2	4	6
1O	0.58	0.58	0.58	0.55	0.55	0.54	0.53	0.53
1E	0.69	0.69	0.70	0.70	0.56	0.55	0.56	0.57
2O	0.63	0.63	0.63	0.64	0.28	0.28	0.28	0.27
2E	0.59	0.59	0.60	0.59	0.31	0.32	0.31	0.31
3O	0.34	0.34	0.34	0.34	0.40	0.40	0.41	0.41
3E	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.31
4O	1.30	1.30	1.29	1.28	1.13	1.11	1.12	1.13
4E	0.62	0.62	0.62	0.62	0.60	0.58	0.58	0.57
5O	0.71	0.71	0.43	0.43	0.65	0.27	0.27	0.27
5E	0.93	0.93	0.57	0.57	0.87	0.36	0.36	0.36
7O	0.82	0.82	0.49	0.50	0.77	0.46	0.47	0.47
7E	0.74	0.74	0.45	0.46	0.76	0.47	0.47	0.47

NOTE:

<sup>a</sup>O = ODD DETECTORS, E = EVEN DETECTORS.

TABLE 24

**COMPARISON OF INITIAL PARAMETERS WITH IMPROVED PARAMETERS**  
**STANDARD DEVIATION OF PULSE VALUES, P**

BAND <sup>a</sup> IC STATE <sup>b</sup>	1		2		3		4		5		7	
	o <sup>1</sup>	i <sup>2</sup>	o <sup>1</sup>	i <sup>2</sup>	o <sup>1</sup>	i <sup>2</sup>	o <sup>1</sup>	i <sup>2</sup>	o <sup>1</sup>	i <sup>2</sup>	o <sup>1</sup>	i <sup>2</sup>
100 O	0.400	0.324	0.255	0.238	0.291	0.252	0.938	0.244	0.200	0.179	0.335	0.327
E	0.539	0.524	0.203	0.173	0.222	0.187	0.510	0.171	0.263	0.251	0.267	0.768
A	0.510	0.424	0.229	0.208	0.257	0.220	0.724	0.208	0.233	0.217	0.301	0.297
110 O	0.582	0.347	0.631	0.283	0.348	0.335	1.289	0.734	0.432	0.379	0.498	0.483
E	0.703	0.546	0.601	0.348	0.308	0.270	0.623	0.733	0.578	0.450	0.458	0.469
A	0.642	0.448	0.618	0.315	0.327	0.302	0.958	0.733	0.509	0.417	0.478	0.478
010 O	0.551	0.248	0.472	0.211	0.252	0.278	0.381	0.230	0.264	0.213	0.342	0.271
E	0.559	0.498	0.435	0.230	0.255	0.242	0.250	0.191	0.324	0.243	0.289	0.290
A	0.555	0.373	0.453	0.221	0.253	0.260	0.306	0.211	0.296	0.229	0.315	0.281
011 O	0.597	0.253	0.529	0.214	0.304	0.284	0.508	0.244	0.351	0.273	0.395	0.385
E	0.604	0.475	0.490	0.247	0.261	0.217	0.387	0.191	0.404	0.310	0.388	0.394
A	0.600	0.364	0.512	0.230	0.282	0.251	0.446	0.218	0.380	0.293	0.391	0.390
111 O	0.642	2.052	0.531	0.321	0.370	1.202	0.884	1.026	0.505	0.329	0.557	0.543
E	0.918	1.762	0.698	1.498	0.405	1.135	0.634	1.140	0.682	0.510	0.584	0.587
A	0.700	1.907	0.614	0.909	0.388	0.721	0.759	0.750	0.599	0.426	0.570	0.565
101 O	0.537	0.361	0.280	0.295	0.410	0.298	1.117	0.243	0.270	0.260	0.471	0.437
E	0.565	0.508	0.311	0.210	0.308	0.214	0.588	0.195	0.368	0.323	0.477	0.433
A	0.551	0.434	0.295	0.252	0.358	0.256	0.852	0.219	0.322	0.293	0.474	0.435
001 O	0.462	0.505	0.227	0.278	0.289	0.244	0.440	0.341	0.174	0.145	0.310	0.274
E	0.628	0.615	0.180	0.157	0.295	0.263	0.471	0.313	0.220	0.209	0.253	0.218
A	0.545	0.560	0.208	0.193	0.292	0.254	0.455	0.327	0.199	0.179	0.282	0.246
000 O	0.426	0.413	0.142	0.141	0.216	0.219	0.197	0.196	0.120	0.112	0.198	0.195
E	0.505	0.575	0.121	0.118	0.206	0.201	0.239	0.235	0.152	0.147	0.197	0.169
A	0.508	0.494	0.131	0.129	0.211	0.210	0.218	0.216	0.137	0.131	0.119	0.182

<sup>a</sup>O = ORIGINAL PARAMETERS, I = IMPROVED PARAMETERS.

<sup>b</sup>O = ODD CHANNELS, E = EVEN CHANNELS, A = ALL CHANNELS.

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where R represents spectral radiance and Q represents digital counts. The resulting error of estimate (Table 25) was about 30 percent higher in every band than the error of estimate obtained using the linear relationship:

$$Q = a + bR$$

Because the relationship of input spectral radiance (R) to the output digital count (Q) is linear, gain can be calculated using only a single lamp state and background data. Table 26 gives the change in gain (in ppt) using only a single lamp state and background relative to using all eight IC lamp states for March 9, 1982, prelaunch data. Table 27 gives the results for postlaunch data collected over Washington, D.C., on November 2, 1982. In both data sets, gain changes associated with lamp 3 are significantly higher than those associated with lamps 1 and 2. These data point to inaccuracies in the prelaunch radiometric calibration of lamp 3.

An examination of pulse values shows that the channels in band 4 saturate in IC state lll. Radiance values for IC state lll in band 4 obtained in the prelaunch calibration are thus in error, and IC state lll should not be included in the linear regressions for the band 4 channels.

#### NET IMAGE

Because the upper limits of noise in the image are comparable to background noise, it was hoped that more precise image radiance measurements could be obtained by using net values. Background readings, however, are available only during scan mirror turnaround. Experimentation with net images based on background readings at two different places in the cycle showed net images in both instances to be as noisy as the overall uncorrected image. Tables 28 and 29 compare the standard deviations, over a scene, of net and gross image readings from prelaunch flooding lamp data and postlaunch data over the Boston harbor (September 10, 1982). Other workers have found, however, that the use of a separate background for each image line, as opposed to a scene-averaged bias for each channel in the calibration process, reduces striping (private communication, D. Fischel, GSFC, and J. Kogut, Research Data Corporation). Of course, the background sample applied to the image needs to be approximately the same as the actual background level present during imaging. To obtain the best estimate of actual background, it is desirable to select background from two regions, one on each side of the image. Because the background level is adjusted during DC restore, the background collect windows need to be located so that DC restore

TABLE 25

POSTLAUNCH RADIOMETRIC CALIBRATION —  
TM LANDSAT-4

REGRESSION ANALYSIS  
ERROR OF ESTIMATE

	<u>TM 1</u>	<u>TM 2</u>	<u>TM 3</u>	<u>TM 4</u>	<u>TM 5</u>	<u>TM 7</u>
LINEAR <sup>a</sup>	0.60	0.67	0.65	0.97	0.22	0.35
QUADRATIC <sup>a</sup>	0.95	1.06	1.01	1.53	0.34	0.54

NOTE:

<sup>a</sup>D.C., NOVEMBER 2, 1982, ID = 4010915140.

TABLE 26

# **PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4**

**CHANGE IN GAIN (ppt)\* FOR CALIBRATION WITH A SINGLE LAMP  
PRELAUNCH DATA, MARCH 9, 1982**

BAND IC STATE USED		1	2	3	4	5	7
001	ODD	37	31	38	36	-0.7	9
	EVEN	41	27	33	32	12	22
010	ODD	16	-5.4	14	6.2	2	12
	EVEN	17	-6.1	19	-14	0.1	17
100	ODD	-2.6	-3.8	-8.0	-4.4	3.7	-1.3
	EVEN	-3.2	-2.4	-13	8.7	3.0	-13

\*REFERENCE: MARCH 9, 1982, PRELAUNCH DATA USING ALL EIGHT IC STATES.

TABLE 27

# **POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4**

**CHANGE IN GAIN (ppt)\* FOR CALIBRATION WITH A SINGLE LAMP  
D.C., NOVEMBER 2, 1982**

IC STATE USED	BAND	1	2	3	4	5	7
001	ODD	37	41	43	47	8.6	20
	EVEN	38	28	36	40	20	27
010	ODD	5.1	-14	0.6	-1.9	-3.2	-7.1
	EVEN	4.6	-14	6.2	-2.3	-4.9	-0.7
100	ODD	-4.4	-2.2	-5.4	1.2	-4.1	3.2
	EVEN	-5.1	-1.7	-8.6	13	3.6	-4.7

\*REFERENCE: D.C., NOVEMBER 2, 1982, WITH ALL EIGHT IC STATES USED IN CALIBRATION.

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TABLE 28

**PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4**  
**STANDARD DEVIATION OF IMAGE DATA (FLOODING LAMP)**  
**(DIGITAL COUNTS)**

BAND <sup>a</sup>	GROSS	GROSS	NET <sup>b</sup>	NET <sup>c</sup>
	ALL SCANS	FORWARD SCANS	ALL SCANS	FORWARD SCANS
1O	1.45	1.44	1.28	1.48
1E	1.50	1.49	1.41	1.51
2O	0.61	0.60	0.59	0.62
2E	0.68	0.69	0.67	0.69
3O	0.86	0.86	0.83	0.89
3E	0.95	0.96	0.93	0.98
4O	0.48	0.48	0.48	0.48
4E	0.53	0.53	0.52	0.53
5O	1.19	1.19	1.19	1.20
5E	1.19	1.19	1.18	1.21
7O	1.40	1.66	1.66	1.68
7E	1.53	1.40	1.40	1.56

## NOTES:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.<sup>b</sup>IMAGE SCAN N — BACKGROUND SCAN N.<sup>c</sup>IMAGE FORWARD SCAN N — BACKGROUND REVERSE SCAN N-1.

361-BA/AB-112a\*1  
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TABLE 29

## POSTLAUNCH RADIOMETRIC CALIBRATION -- TM LANDSAT-4

STANDARD DEVIATION OF IMAGE DATA, BOSTON WATER SCENE, SEPTEMBER 10, 1982  
(DIGITAL COUNTS)

BAND <sup>a</sup>	GROSS	GROSS	NET <sup>b</sup>	NET <sup>c</sup>
	ALL SCANS	FORWARD SCANS	ALL SCANS	FORWARD SCANS
1O	1.51	1.46	1.47	1.46
1E	1.72	1.68	1.60	1.67
2O	0.59	0.58	0.58	0.58
2E	0.66	0.65	0.65	0.65
3O	0.84	0.81	0.80	0.83
3E	0.94	0.96	0.93	0.98
4O	0.46	0.46	0.47	0.46
4E	0.46	0.46	0.47	0.46
5O	0.92	0.93	0.93	0.93
5E	0.84	0.85	0.84	0.86
7O	1.13	1.12	1.11	1.16
7E	1.06	1.05	1.05	1.08

## NOTES:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.<sup>b</sup>IMAGE SCAN N -- BACKGROUND SCAN N.<sup>c</sup>IMAGE FORWARD SCAN N -- BACKGROUND REVERSE SCAN N-1.361-DA/AB-112h\*)  
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does not occur between the background window and the image to which the background is applied. Table 30 gives the present collect windows and proposed windows for achieving this goal. The locations for the proposed windows were derived using information from the scan timeline presented in Barker, Abrams, et al. (1984).

#### SEPARATE PROCESSING FOR FORWARD AND REVERSE SCANS

Differences in forward and reverse calibration data arise primarily from calibration pulse shape and pulse integration techniques (Barker, Abrams, et al., 1984). The pulse in band 4 (Figure 9) is shaped like a right triangle on top of a rectangle. The pulse center is located so far from the pulse peak that a small variation in pulse shape could cause some of the minor frames near the pulse peak to fall outside the pulse integration region. The use of a wider pulse integration width reduces differences in forward and reverse calibration pulse values (Tables 31 and 32). The magnitude of forward-reverse differences in calibration pulse in band 4 (from 0 to 4 counts) is highly variable as a result of sensitivity to small changes in pulse shape. Figures 10 and 11 show the forward-reverse pulse differences for the 100 IC state, band 4, channel 9, in the March 9, 1982, pre-launch data and the D.C., November 2, 1982, postlaunch data. A secondary cause of calibration pulse forward-reverse differences possibly results from a gradual drift in the background counts during a scan.

Differences in forward and reverse background values, averaged over a scene, tend to vary widely (Table 33) but are occasionally as high as a count. The source of the differences must be investigated. One possible explanation is the gradual drift in the background mentioned above. Another explanation is that background data were collected from the section of the scan cycle where background levels are unstable. This region, known as DC restore, is the region in which the TM restores the background toward the nominal value of 2 digital counts.

Prelaunch flooding lamp data collected from 52 minor frames in the middle of the scan show, as expected, only small (less than 0.35 digital count) forward and reverse differences (Table 34). Forward-reverse differences in postlaunch image data arise from variations in the background discussed above. Table 35 gives forward-reverse differences taken from 512 minor frames of B data (Barker, Gunther, et al., 1984).

TABLE 30

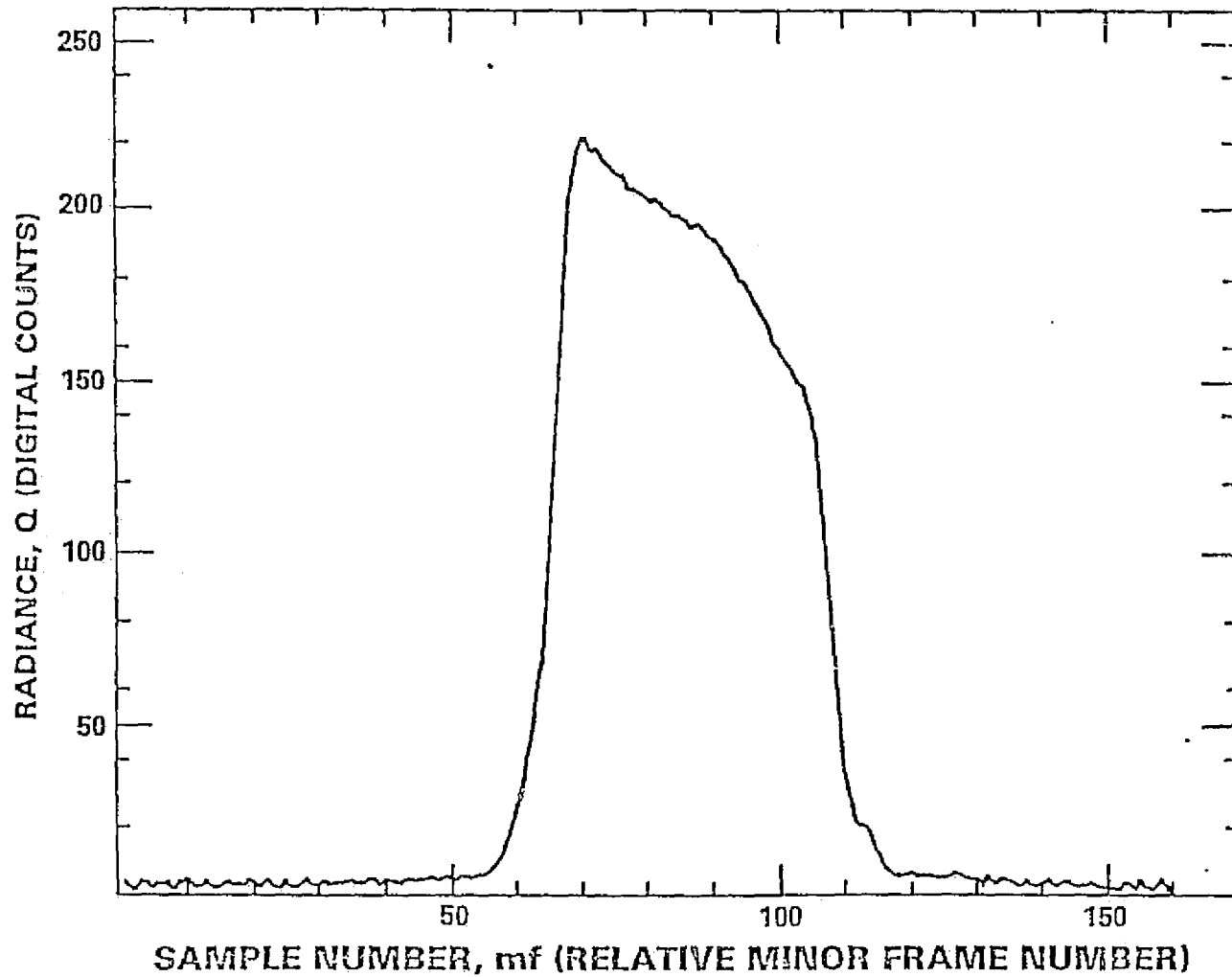
# **BACKGROUND COLLECT WINDOWS (52 MINOR FRAMES WIDE)**

PERIOD	FIRST COLLECT		SECOND COLLECT	
	FORWARD SCAN (MINOR FRAMES)	REVERSE SCAN (MINOR FRAMES)	FORWARD SCAN (MINOR FRAMES)	REVERSE SCAN MINOR FRAMES)
LAUNCH TO PRESENT	6543 (52)	7089 (52)	—	—
PROPOSED	6469 (24)	6749 (28)	6925 (28)	7205 (24)

9191-ABR-(18f)

FIGURE 9

RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM4 CHANNEL 8 FORWARD SCAN, MARCH 9, 1982, VACUUM



361-BA/AB-(50b)  
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TABLE 31

# DIFFERENCE BETWEEN FORWARD AND REVERSE AVERAGES (DIGITAL COUNTS)

D.C., NOVEMBER 2, 1982 — USING STANDARD PARAMETERS

		TM 1	TM 2	TM 3	TM 4	TM 5	TM 7
CHANNEL	1	—	—0.74	0.62	1.85	0.67	0.96
	2	—0.08	—0.13	0.10	0.68	0.83	0.91
	3	0.28	0.29	0.30	1.98	—	—0.03
	4	0.29	—0.09	0.13	0.38	0.05	0.12
	5	0.25	0.15	0.22	1.49	—0.09	—
	6	0.29	—0.06	—0.06	0.67	—0.12	0.03
	7	0.37	0.15	0.30	1.30	—0.14	0.54
	8	0.20	0.13	0.12	0.54	—0.10	—0.06
	9	0.29	0.22	0.13	1.36	—0.08	—0.09
	10	0.32	—0.18	0.09	0.18	—0.23	—0.07
	11	0.37	0.13	0.19	1.45	—0.10	—0.08
	12	0.01	0.04	0.00	0.36	—0.26	—0.06
	13	0.27	0.04	0.15	1.52	—0.17	—0.21
	14	0.11	—0.32	—0.02	0.70	—0.41	—0.18
	15	0.62	0.04	0.04	1.24	—0.22	—0.49
	16	0.11	—0.20	0.01	0.62	—0.34	—0.21
MEANODD		0.04	0.03	0.24	1.53	—0.02	0.07
MEANEVN		0.15	—0.10	0.04	0.52	—0.07	0.05
MEANALL		0.10	—0.03	0.14	1.02	—0.05	0.06
MEANODD SD		0.88	0.32	0.17	0.26	0.30	0.46
MEANEVN SD		0.14	0.14	0.07	0.18	0.39	0.36
MEANALL SD		0.61	0.25	0.16	0.56	0.34	0.40
MEAN SPSD		0.15	0.06	0.04	0.14	0.09	0.10

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TABLE 32

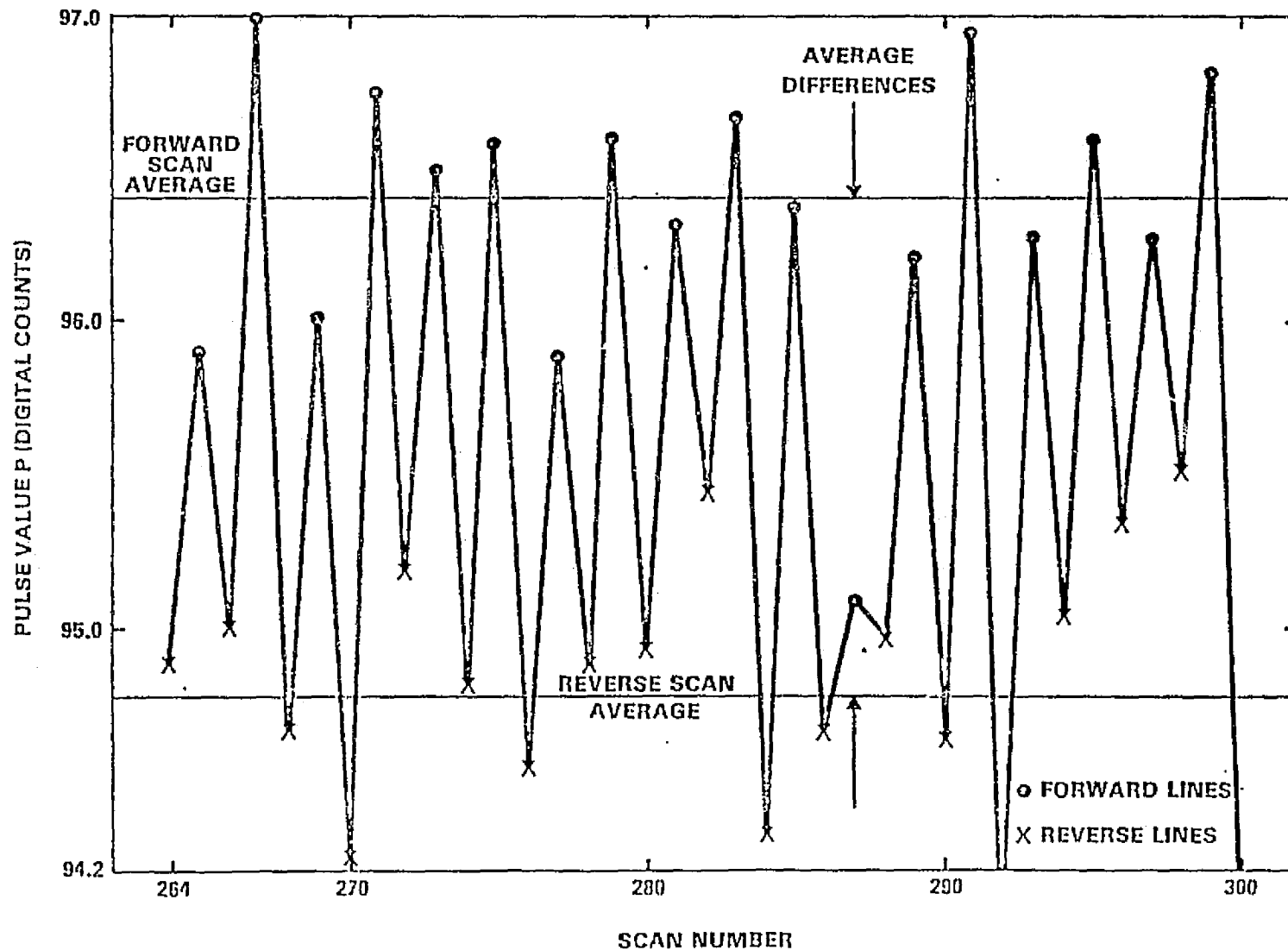
# DIFFERENCE BETWEEN FORWARD AND REVERSE AVERAGES (DIGITAL COUNTS)

D.C., NOVEMBER 2, 1982 — USING OPTIMIZED PARAMETERS

		<u>TM 1</u>	<u>TM 2</u>	<u>TM 3</u>	<u>TM 4</u>	<u>TM 5</u>	<u>TM 7</u>
CHANNEL	1	—	—0.96	—0.05	0.09	0.61	0.90
	2	0.36	0.04	0.03	0.23	0.89	0.86
	3	0.55	0.27	0.17	0.47	—	—0.06
	4	0.40	—0.30	0.10	0.17	0.12	0.07
	5	0.41	0.11	0.10	0.23	—0.06	—0.04
	6	0.69	0.04	—0.01	0.12	—0.10	0.02
	7	0.52	0.06	0.10	0.23	—0.15	0.42
	8	0.38	0.01	0.05	0.05	—0.10	—0.08
	9	0.48	0.09	0.13	0.38	—0.14	—0.13
	10	0.44	—0.15	—0.02	0.04	—0.26	—0.14
	11	0.48	—	—	0.05	—0.18	—0.14
	12	0.07	—0.08	—0.03	0.03	0.26	—0.09
	13	0.51	—0.04	—0.02	—0.03	—0.23	—0.23
	14	0.16	—0.33	—0.15	—0.05	—0.45	—0.23
	15	0.54	—0.07	—0.04	0.08	—0.14	—0.43
	16	0.11	—0.29	—0.09	—0.15	—0.29	—0.27
MEANODD		0.44	—0.06	0.04	0.19	—0.04	0.03
MEANENV		0.33	—0.13	—0.01	0.05	—0.05	0.01
MEANALL		0.38	—0.10	0.01	0.12	—0.05	0.02
MEANODD SD		0.18	0.38	0.09	0.17	—0.29	0.42
MEANENV SD		0.20	0.16	0.08	0.12	0.42	0.36
MEANALL SD		0.19	0.28	0.08	0.16	0.35	0.38
MEAN SPSD		0.04	0.07	0.02	0.04	0.09	0.09

FIGURE 10

# PRELAUNCH TM LANDSAT-4 RADIOMETRIC CALIBRATION BETWEEN-LINE VARIABILITY OF IC PULSE TM4, CHANNEL 9, LAMP 100, MARCH 5, 1982



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FIGURE 11

POSTLAUNCH TM LANDSAT-4 RADIOMETRIC CALIBRATION  
BETWEEN-LINE VARIABILITY OF IC PULSE  
TM4, CHANNEL 9, LAMP 100, D.C., NOVEMBER 2, 1982

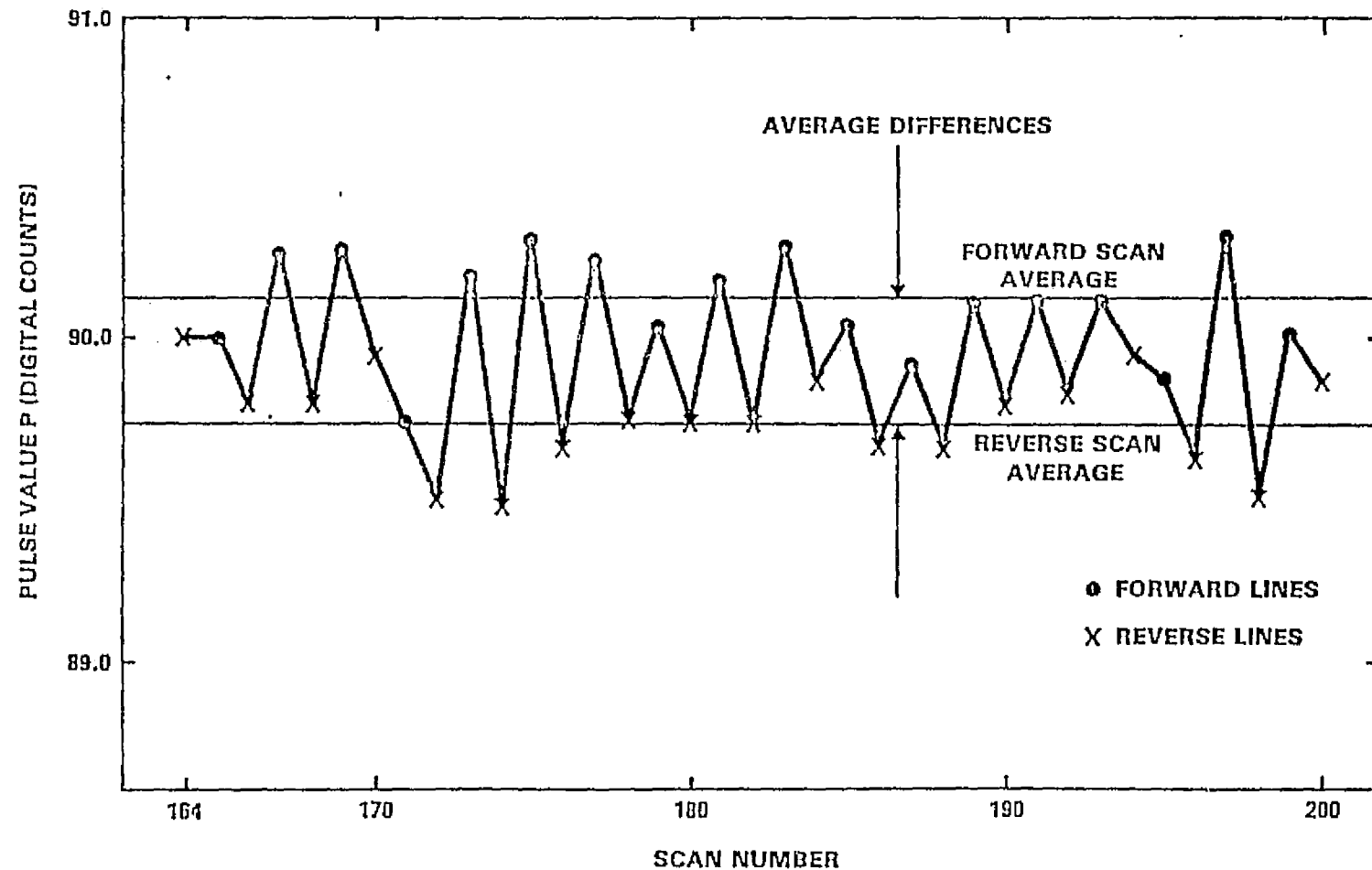


TABLE 33

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
DIFFERENCE BETWEEN FORWARD AND REVERSE (F-R) BACKGROUND  
DATA (DIGITAL COUNTS)**

BAND <sup>a</sup>	FLOODING LAMP	WATER	NE ARKANSAS	FT. DODGE	D. C.	HAMILTON, MONTANA	FT. PIERCE, FLORIDA
1O	0.08	-0.67	-0.16	-0.54	-1.04	-0.87	-0.56
1E	0.10	-0.64	-0.11	-0.50	-1.01	-0.81	-0.50
2O	0.11	-0.03	0.01	-0.08	-0.22	-0.19	-0.00
2E	0.08	-0.03	0.03	-0.08	-0.22	-0.19	0.02
3O	0.18	-0.00	0.01	-0.04	-0.25	-0.24	0.04
3E	0.13	-0.02	0.07	-0.04	-0.27	-0.27	0.09
4O	0.12	0.55	-0.50	-0.59	-0.07	-0.20	0.33
4E	0.14	0.64	-0.55	-0.64	-0.06	-0.23	0.41
5O	-0.01	-0.03	-0.04	-0.05	-0.04	-0.03	-0.03
5E	-0.02	-0.02	-0.05	-0.04	-0.04	-0.03	-0.02
7O	-0.09	-0.05	-0.04	-0.05	-0.04	-0.03	-0.02
7E	0.02	0.00	-0.04	-0.02	-0.04	-0.02	0.00

NOTE:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

**PRELAUNCH TM LANDSAT-4 RADIOMETRIC CALIBRATION**  
**AVERAGE DIFFERENCES BETWEEN FORWARD AND REVERSE VIDEO**  
**MIDSCAN**  
**(DIGITAL COUNTS)**

DATE BAND	2-22-82	2-23-82	3-3-82	3-4-82	3-5-82	3-7-82	3-9-82	3-17-82	3-17-82	3-22-82	4-23-82
1	-0.038	-0.082	-0.112	-0.190	-0.149	-0.092	-0.119	0.056	0.020	0.041	-0.535
2	-0.041	-0.072	-0.175	-0.189	-0.100	-0.083	-0.091	0.033	0.021	0.013	-0.613
3	-0.105	-0.182	-0.349	-0.337	-0.228	-0.213	-0.226	0.025	0.008	0.021	0.046
4	-0.061	-0.112	-0.142	-0.165	-0.118	-0.106	-0.117	0.023	0.012	0.020	0.241
5	—	—	—	—	—	0.015	0.011	—	—	—	—
7	—	—	—	—	—	0.021	0.010	—	—	—	—

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TABLE 35

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
DIFFERENCE BETWEEN FORWARD AND REVERSE (F-R) IMAGE DATA  
(DIGITAL COUNTS)**

BAND <sup>a</sup>	SCENE						
	FLOODING LAMP	WATER	NE ARKANSAS	FT. DODGE	BOSTON	D. C.	HAMILTON, MONTANA
1O	-0.06	-0.85	-0.27	-0.40	-1.63	-0.71	4.20
1E	-0.10	-0.90	-0.24	-0.40	-1.61	-0.71	3.89
2O	-0.07	-0.10	-0.08	-0.10	-1.07	-0.24	3.11
2E	-0.10	-0.13	0.10	-0.12	-1.09	-0.25	2.97
3O	-0.17	-0.01	0.20	-0.07	-1.42	-0.05	3.78
3E	-0.24	-0.10	0.26	-0.18	-1.48	-0.05	3.61
4O	-0.10	-0.01	-2.00	0.02	-3.28	0.77	3.09
4E	-0.11	0.00	-2.70	-0.24	-3.21	0.72	2.83
5O	0.01	0.01	-0.12	-0.07	-2.79	1.73	0.54
5E	0.00	0.01	-0.09	-0.43	-2.64	1.69	0.54
7O	-0.03	-0.02	0.20	-0.01	-1.33	0.39	0.20
7E	0.03	0.06	0.30	-0.20	-1.15	0.37	0.29

NOTE:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

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These results suggest that the external calibration data should be examined again to obtain separate nominal gains and offsets for forward and reverse scans. In postlaunch processing, forward and reverse calibration pulse data could then be used to generate separate forward and reverse scan radiometric lookup tables (RLUTs).

### CONCLUSIONS

It is difficult to separate changes of the channels with time from changes of the IC system with time. As indicated in this study, the channels within a primary plane band change gain as a self-consistent group (within 0.6 percent). The gains of the cold focal plane channels in a given band change as a group relative to a postlaunch reference (within 1.5 percent), but vary widely relative to a prelaunch reference (up to 5 percent in band 5 and up to 3 percent in band 7). The primary focal plane channels decrease in gain during the first 70 days after launch (6 percent in bands 1 and 2, 8 percent in band 3, and 3 percent in band 4), but stabilize in October 1982. Gain in the cold focal plane channels oscillates with time with a variability of up to 7 percent in band 5 and 5 percent in band 7. When a prelaunch reference is used, lamps 1 and 3 behave consistently, but lamp 2 does not. When a postlaunch reference is used, all three lamps are mutually consistent.

The changed relationship of lamp 2 to the other lamps since prelaunch calibration implies that the lamps are not stable with time. On the other hand, the difference in the gain change pattern of the channels in the cold focal plane and those in the primary focal plane would indicate that the observed gain change is due primarily to the changes in the channels. Perhaps in the future it would be desirable to "burn-in" TM before absolute calibration. The cause of the oscillation in gain in the cold focal plane needs to be better understood.

Variations in the background range from 0.5 to 1.27 digital counts. The degree to which this variation is systematically related to the dark current (DC) restore cycle must be investigated. Coherent noise is strongest in band 1, channels 2, 3, 4, 5, 6, 8, 14, and 16, band 3, channels 4 and 8, and band 4, channels 4 and 5, with peak-to-peak amplitudes ranging from 0.7 to 1.4.

## RECOMMENDATIONS

Brief recommendations are given below; extensive recommendations are given in the paper by Barker (1984).

### GROUND SEGMENT PROCESSING SYSTEM

At present, the continued use of the IC to calibrate is preferred to the use of prelaunch nominal gains and offsets. Because the channels in a band vary as a group, it would be possible to assess the time changes in sensitivity of all the channels in a given band by monitoring a single representative channel with the IC. To improve the use of the IC system in determining gains and offsets, the following procedural changes are recommended:

- Improvement of windows for background extraction to obtain a better estimate of background applicable to an image
- Improvement of the pulse location algorithm so that a few minor frames of partial image data at the edge of the calibration window do not affect results
- Use of a wider, band-dependent pulse integration width
- Exclusion from the averaged pulse value,  $Q$ , of the four scans preceding an IC state transition
- Elimination in the regression analysis of the four states involving lamp 3 (001, 101, 011, 111) until calibration data from lamps 1 and 2 can be used to estimate new spectral radiances for these states
- Separate processing of forward and reverse scans

The first five suggestions would be implemented during the Scrounge era; the last is a major change, best implemented under the TM Image Processing System (TIPS).

### GROUND SEGMENT DATA ANALYSIS

The degree of uniformity in the shutter flag movement could be evaluated by monitoring the minor frame separation of the channel 1 and channel 16 calibration pulse centers. The separation in minor frames of the calibration pulse centers

of the cold focal plane (CFP) channels from the end of the scan line signal would be a sensitive indicator of slight movements in the cold focal plane. IC data could be used to investigate movements of the CFP. IC pulse shape is particularly sensitive to movement of the CFP along the axis defined by the following two planes: (1) the plane of the shutter movement and (2) the plane containing the shutter arm and optical axis of the TM. The location of the pulse (in minor frames) relative to shutter obscuration of the image indicates movement of the CFP in the direction parallel to the shutter movement. Movement of the CFP along the optical axis would be difficult to detect with IC data.

Variations in image data can be used to study variations in the background over a scan. Target variation is removed by computing, for several images, scene-wide averages for each channel in each direction for each horizontal position in the scan. Part of the variation along the scan arises from differences in solar zenith angles for the eastern and western parts of an image. However, because background drift depends on scan direction, and solar illumination is independent of scan direction, these two effects can be separated.

#### SOFTWARE

A software tool for automatically monitoring Landsat-4 TM data needs to be developed. Quantities to be monitored should include channel gains and offsets, background noise, digital count differences between forward and reverse scans in background and integrated calibration pulse values, and self-consistency checks of the IC states. A suitable program to use as a basis for the TM monitor would be TRAPP, the software analysis tool designed and developed by the authors, which was used to obtain the data presented in this paper. TRAPP also needs to be enhanced to generate a history file. The history file should include the above-mentioned quantities plus additional pertinent data such as instrument temperatures and pulse and background window locations. Further study both to better characterize the radiometric performance of the TM and to determine methods for improving the calibration procedures will increase knowledge of the absolute radiometric values in TM scenes.

## FLIGHT SEGMENT OPERATIONS

### Scrounge Era

The temperature of various parts of the TM affects channel sensitivity and IC system output. The indium antimonide detectors in the mid-IR bands are sensitive to the shutter flag temperature as well as the temperature of the cold focal plane itself. The IC system output shifts to shorter wavelength with higher lamp filament temperatures. An increase in temperature at the regulatory photodiode in the lamp circuit tends to make the photodiode more sensitive to lamp output and hence to reduce the output of the lamp. To assess the magnitude of the effect of temperature variations on the protoflight TM, the duration of the TM duty cycle should be varied, so that data at different operating temperatures can be collected.

### TIPS Era

Gain measured using only lamp 1 and background data agrees with gain measured using all eight IC states within 0.9 percent. The possibility of lamp burnout can be reduced while accuracy is preserved by doing the following: Every pass, leave lamp 1 on and the automatic sequencer off; once a week, turn the automatic sequencer on, and check lamp 1 against the other two lamps.

## ACKNOWLEDGMENT

The authors extend a special thanks to Barbara Jeffe for her assistance in programming the TRAPP software package and for supervising the data processing team.

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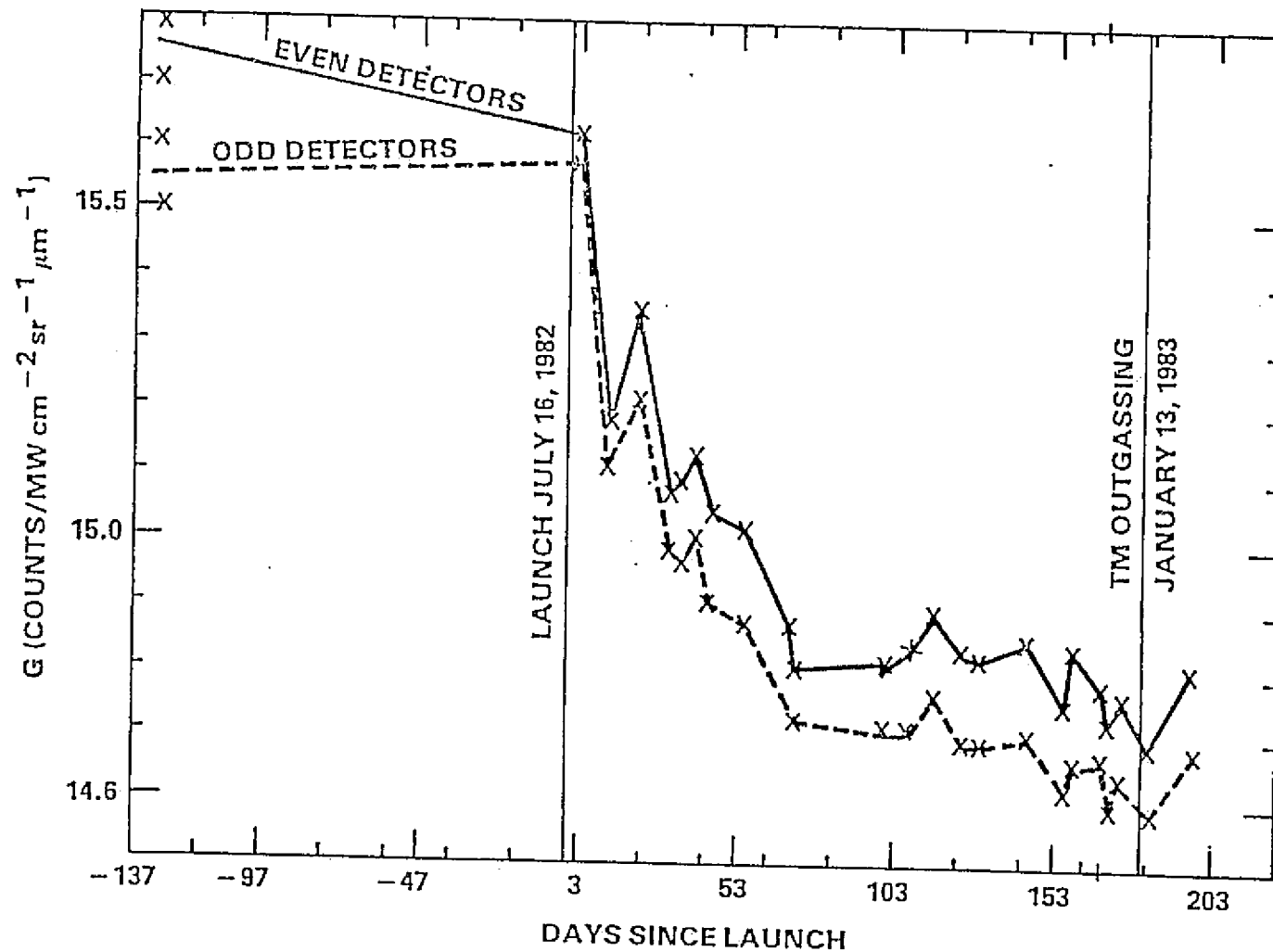
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## APPENDIX - SUPPLEMENTAL DATA

The figures and tables presented here provide detailed information that was summarized in the paper. Figures A-1 through A-6 show channel sensitivity as a function of time. Figures A-7 through A-17 show pulse averages versus scan number. Tables A-1 through A-5 give the changes in the pulse averages of the single-lamp states relative to the March 9, 1982, prelaunch reference. Tables A-6 through A-10 provide similar information using the Washington, D.C., November 2, 1982, postlaunch reference. Changes in gain (parts per thousand) on five separate dates relative to March 9, 1982, are given for each channel in bands 2, 5, and 7 in Tables A-11, A-12, and A-13, respectively. Tables A-14 and A-15 give typical background noise in postlaunch and prelaunch data. Table A-16 lists analog-to-digital converter bin sizes for each digital level in band 1, channel 1.

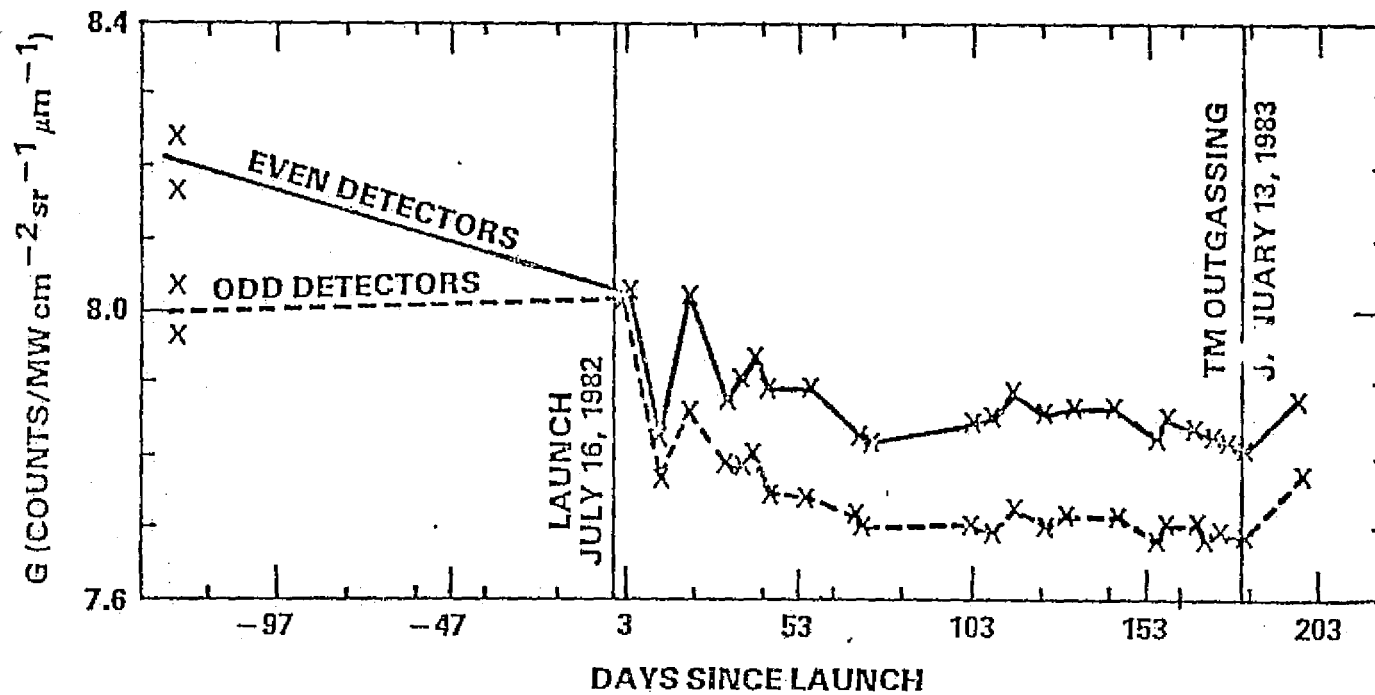
FIGURE A-1  
 POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
 TM1 GAIN IN COUNTS/SPECTRAL RADIANCE AS A FUNCTION OF TIME



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FIGURE A-2

**POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4**  
**TM2 GAIN IN COUNTS/SPECTRAL RADIANCE AS A FUNCTION OF TIME**



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FIGURE A-3

POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
 TM3 GAIN IN COUNTS/SPECTRAL RADIANCE AS A FUNCTION OF TIME

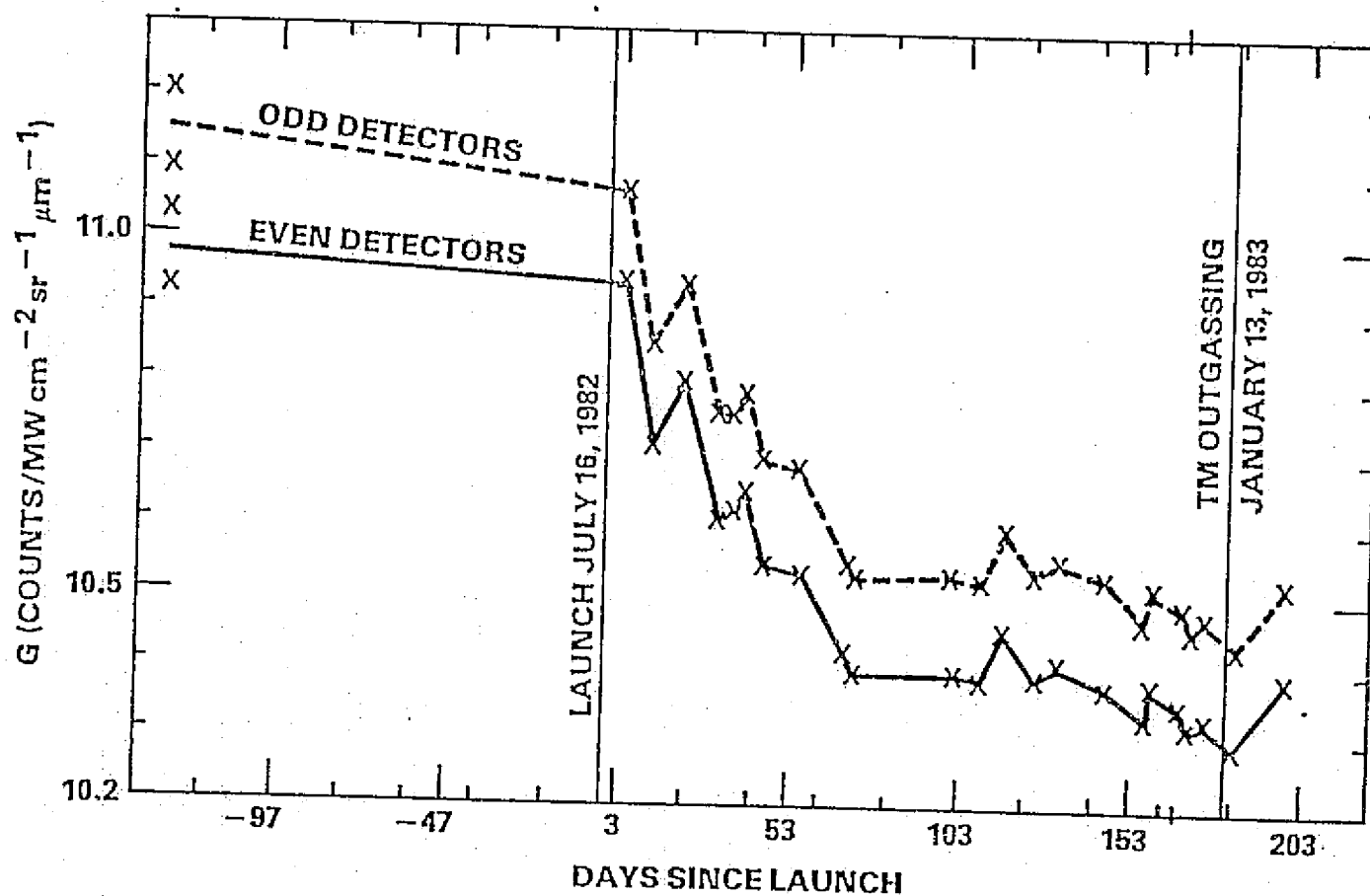
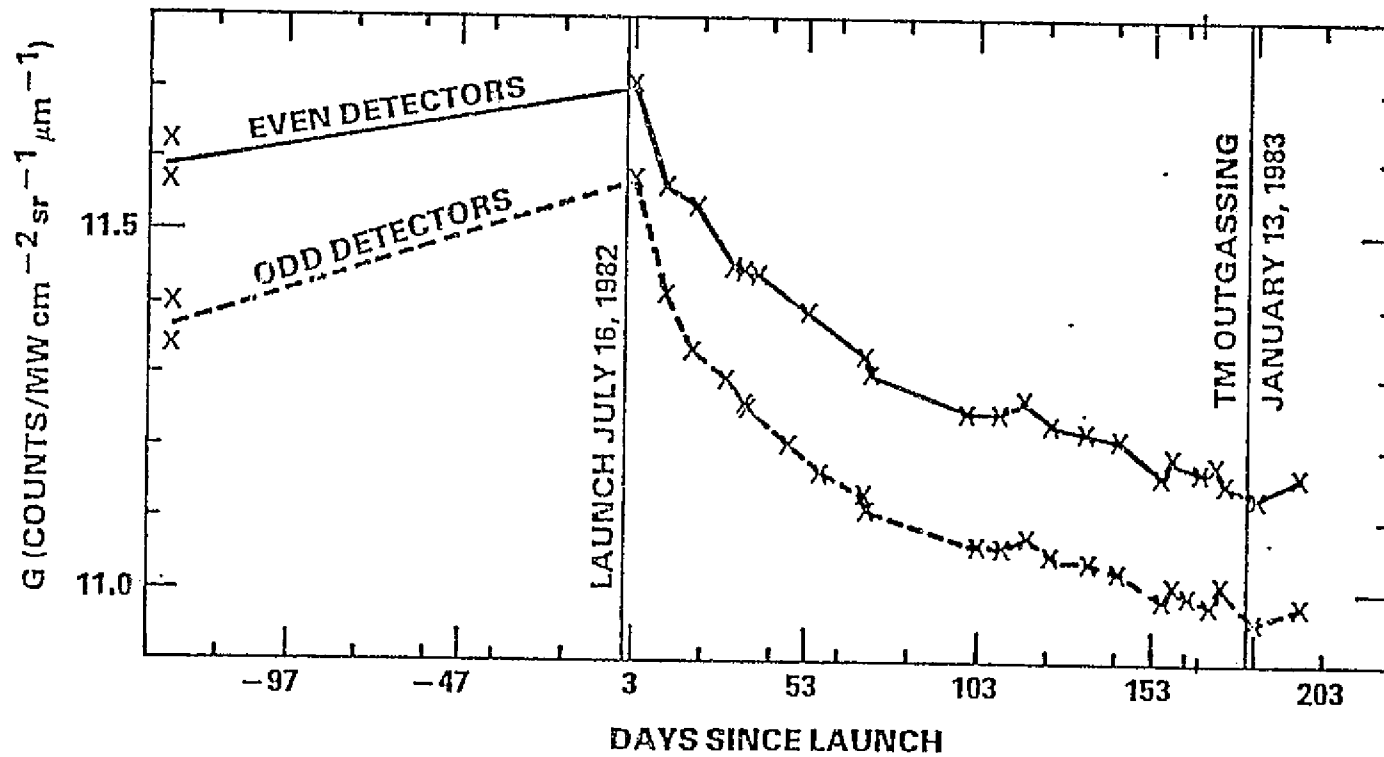


FIGURE A-4

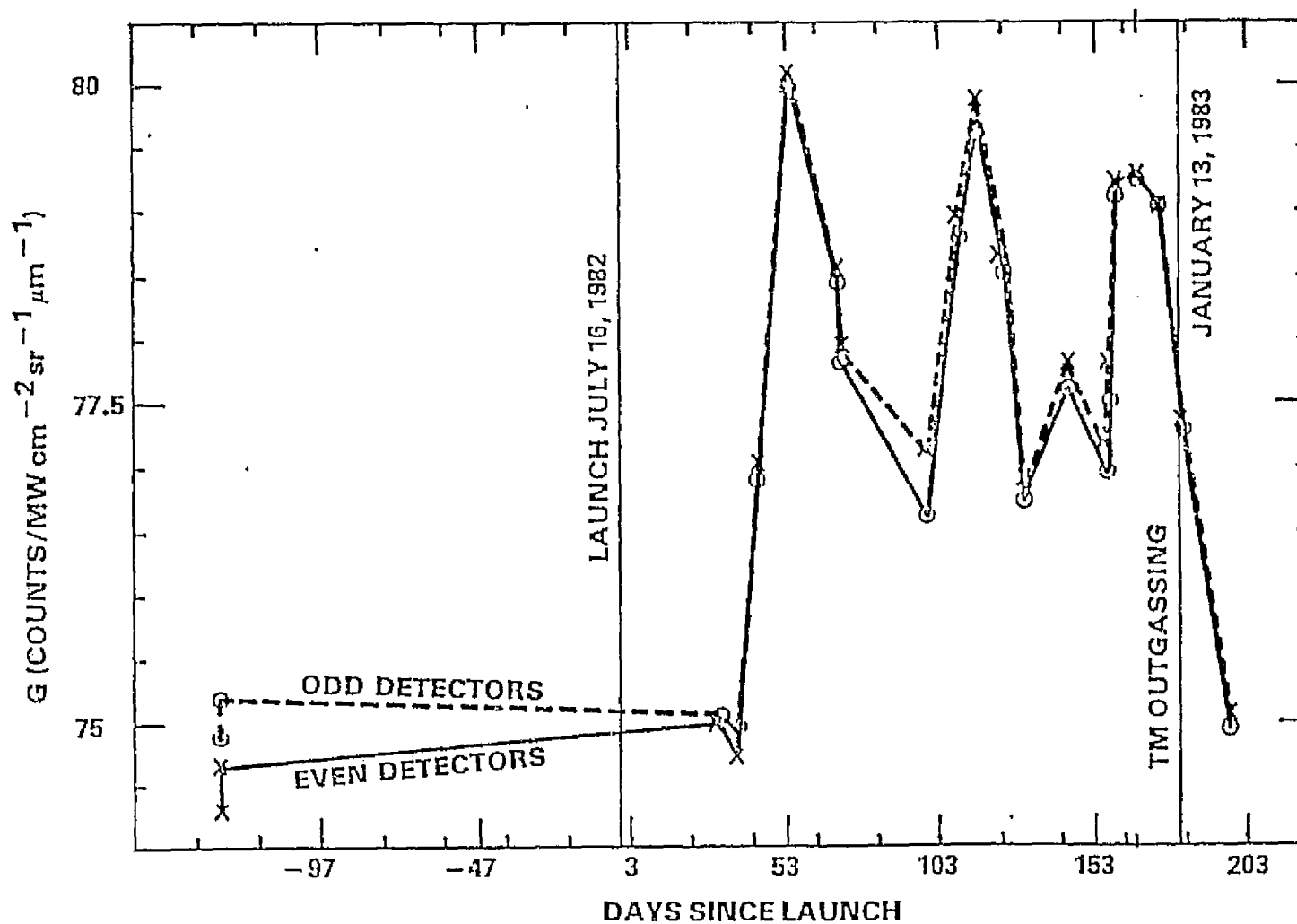
POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
TM4 GAIN IN COUNTS/SPECTRAL RADIANCE AS A FUNCTION OF TIME



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FIGURE A-5

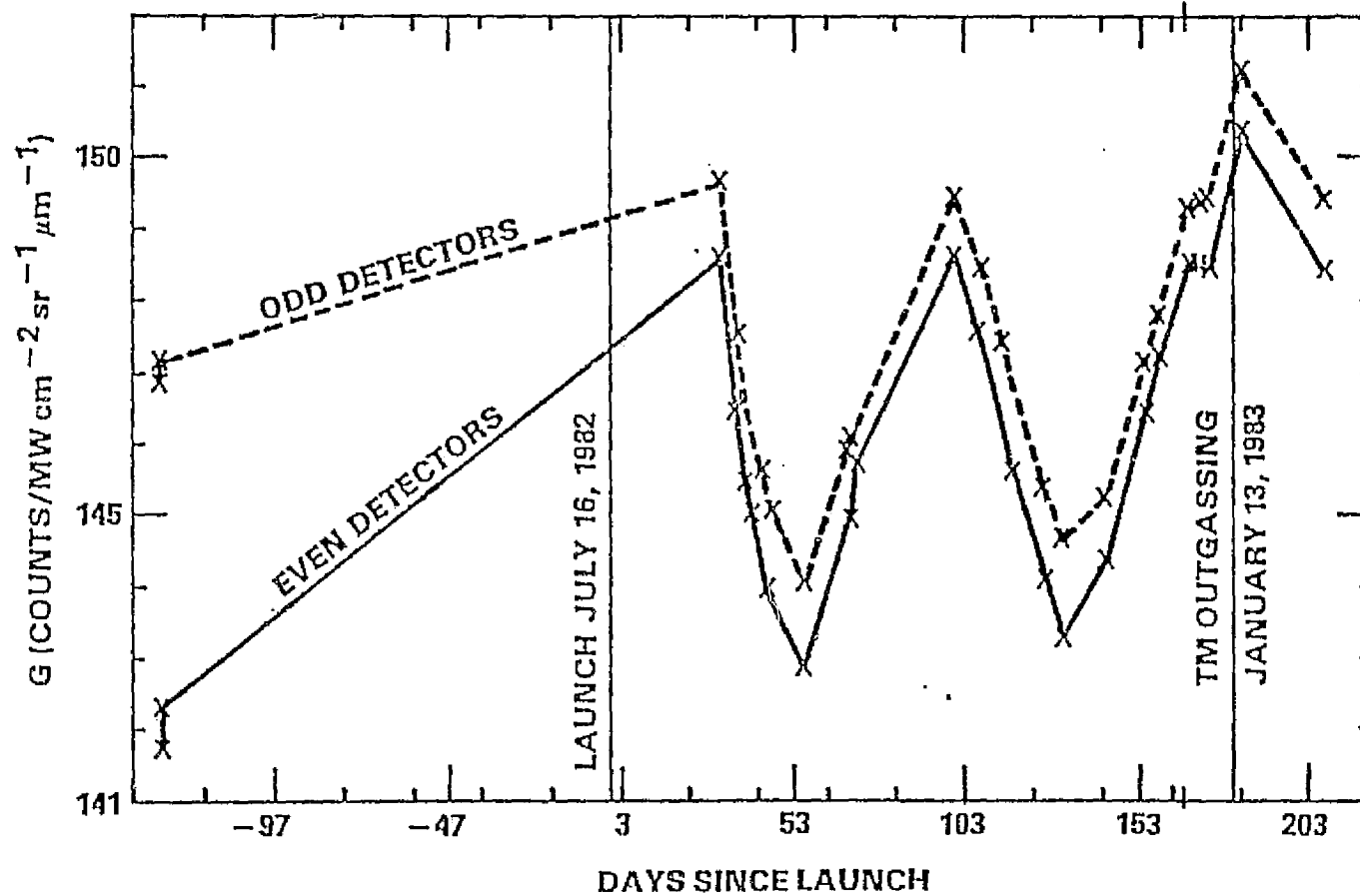
POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
TM5 GAIN IN COUNTS/SPECTRAL RADIANCE AS A FUNCTION OF TIME



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FIGURE A-6

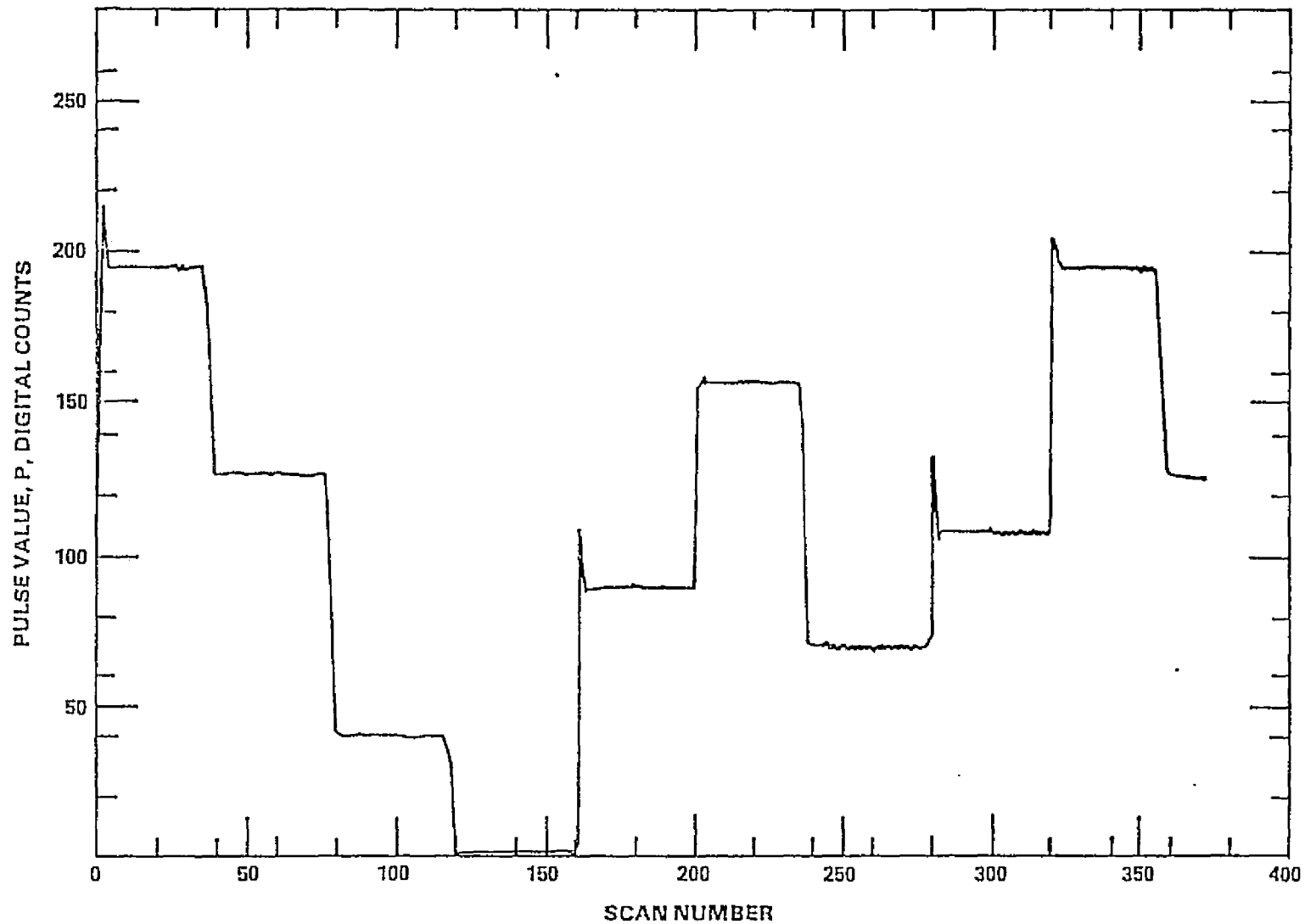
POSTLAUNCH RADIOMETRIC CALIBRATION—TM LANDSAT-4  
TM7 GAIN IN COUNTS/SPECTRAL RADIANCE AS A FUNCTION OF TIME



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FIGURE A-7

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM2 CHANNEL 9 ID = 40109-15140 PULSE VALUES



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FIGURE A-8

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM3 CHANNEL 9 ID = 40109-15140 PULSE VALUES

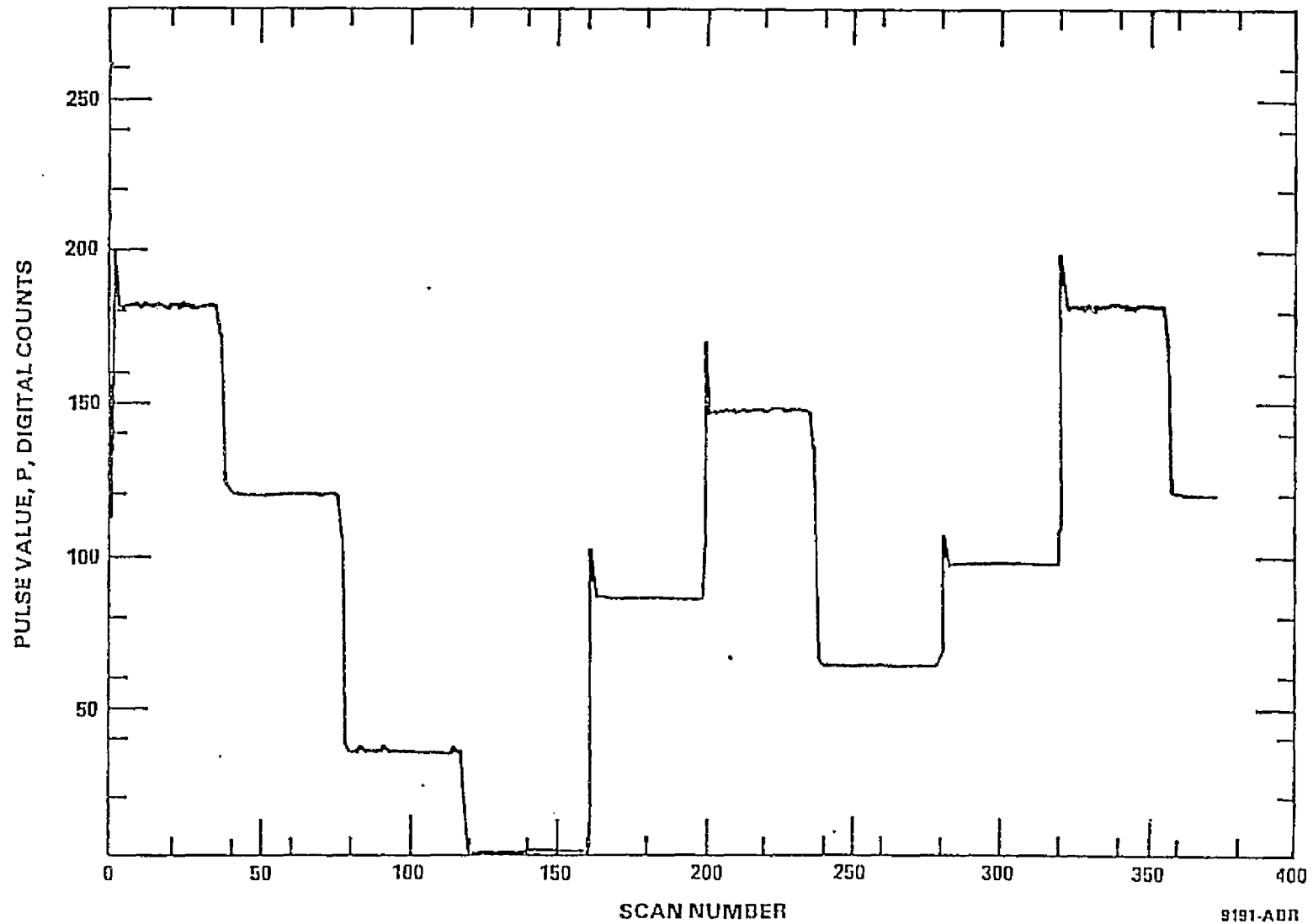
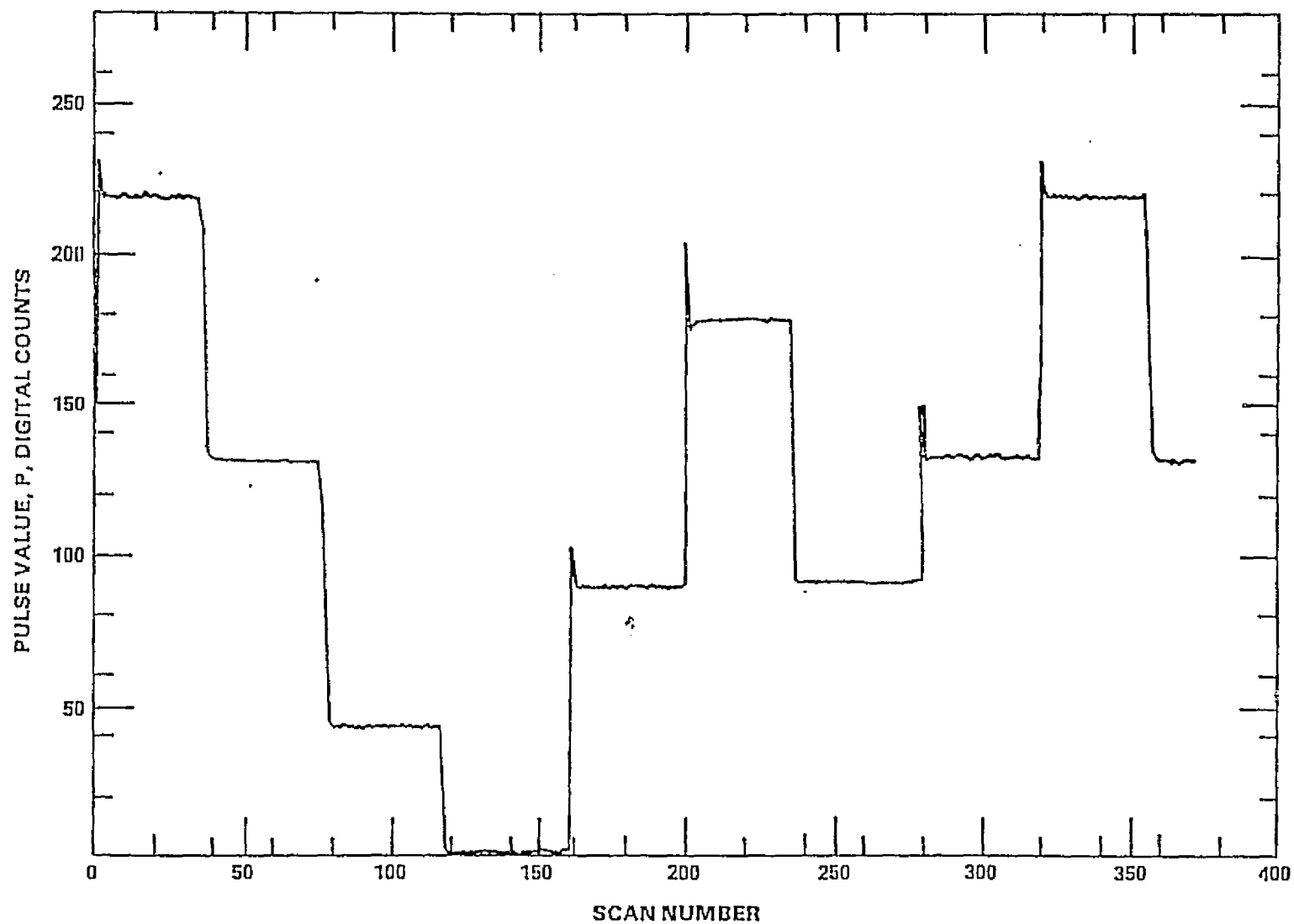


FIGURE A-9

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM4 CHANNEL 9 ID = 40109-15140 PULSE VALUES

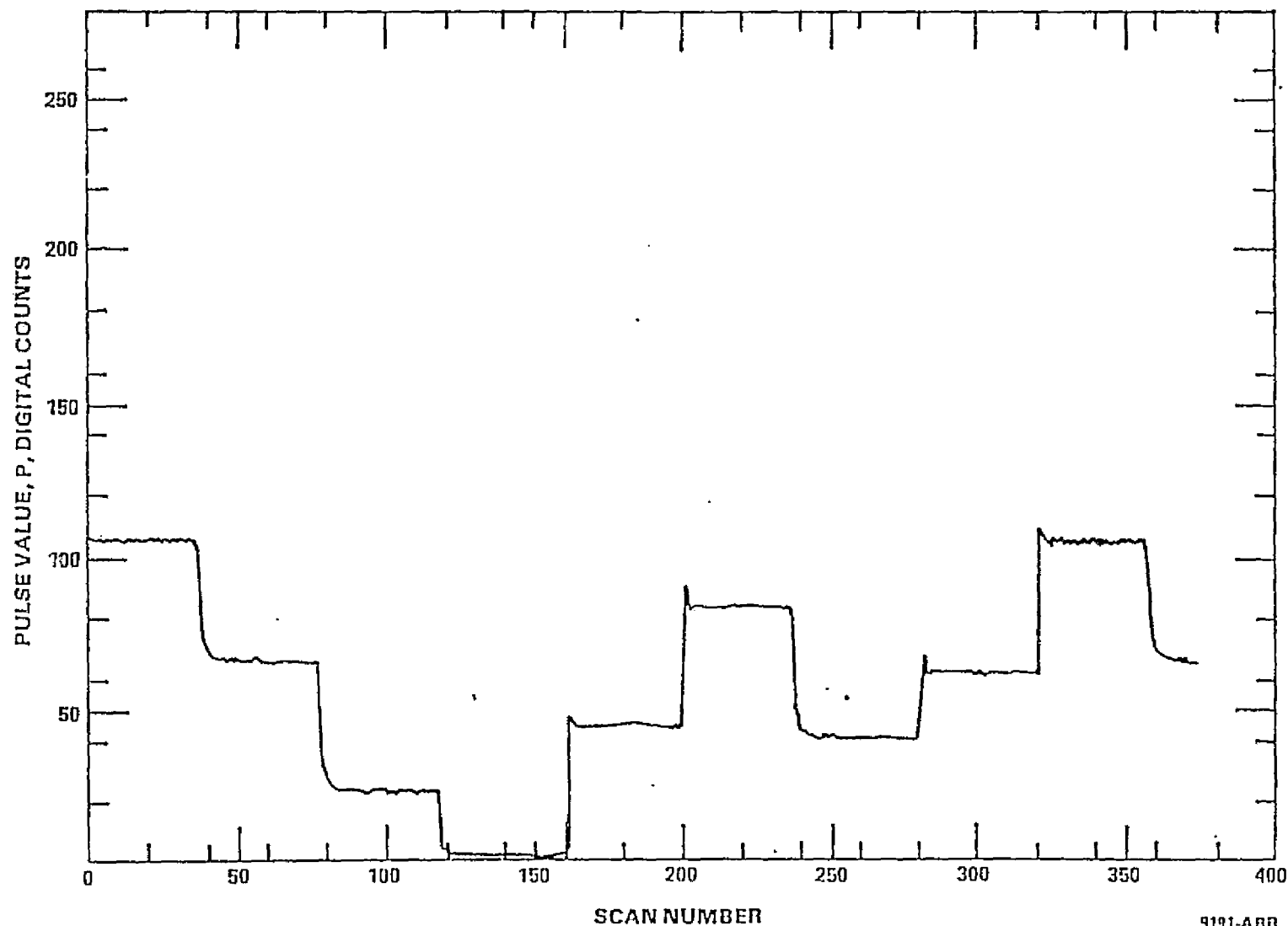


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FIGURE A-10

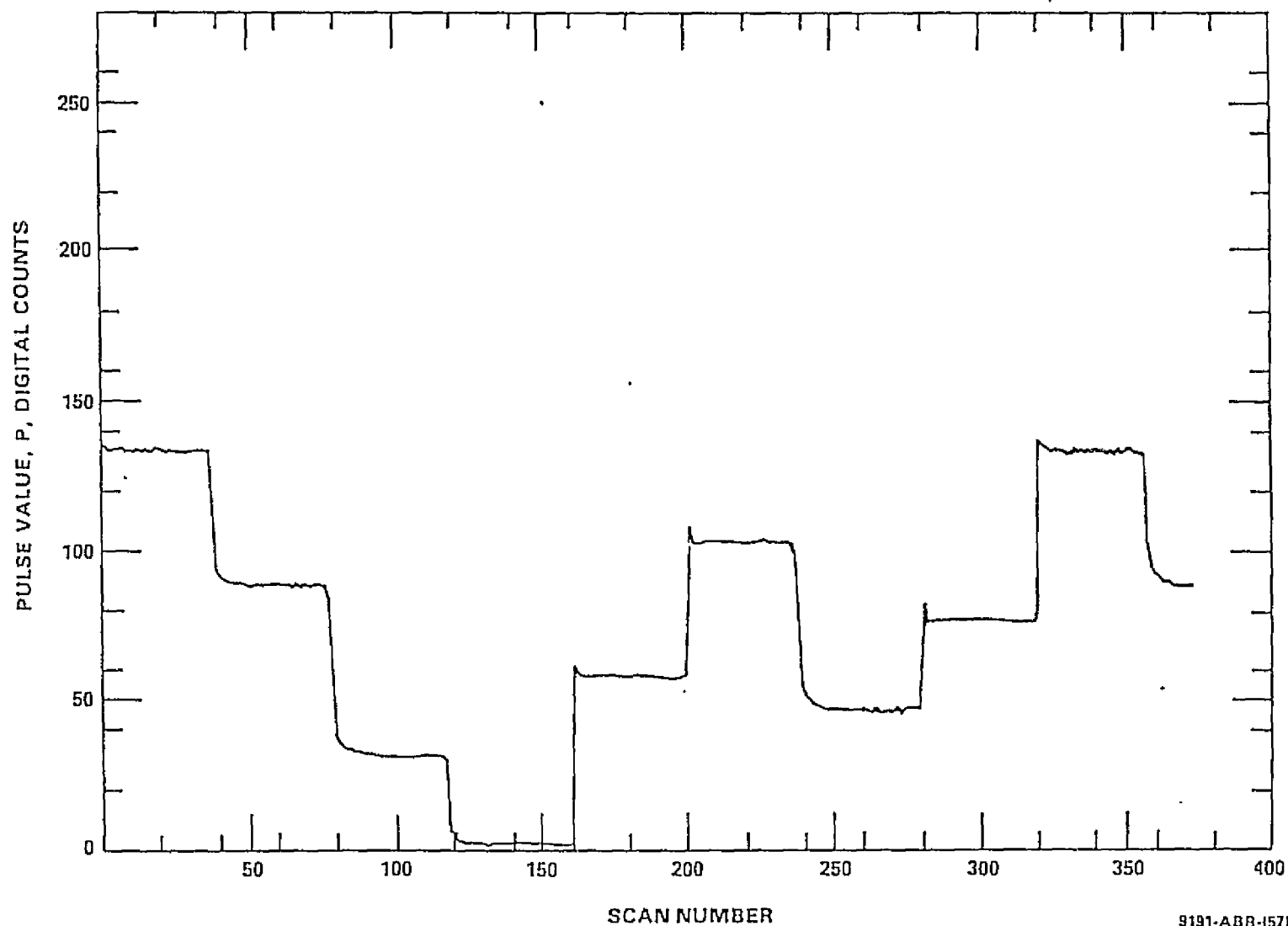
POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM5 CHANNEL 9 ID = 40109-15140 PULSE VALUES



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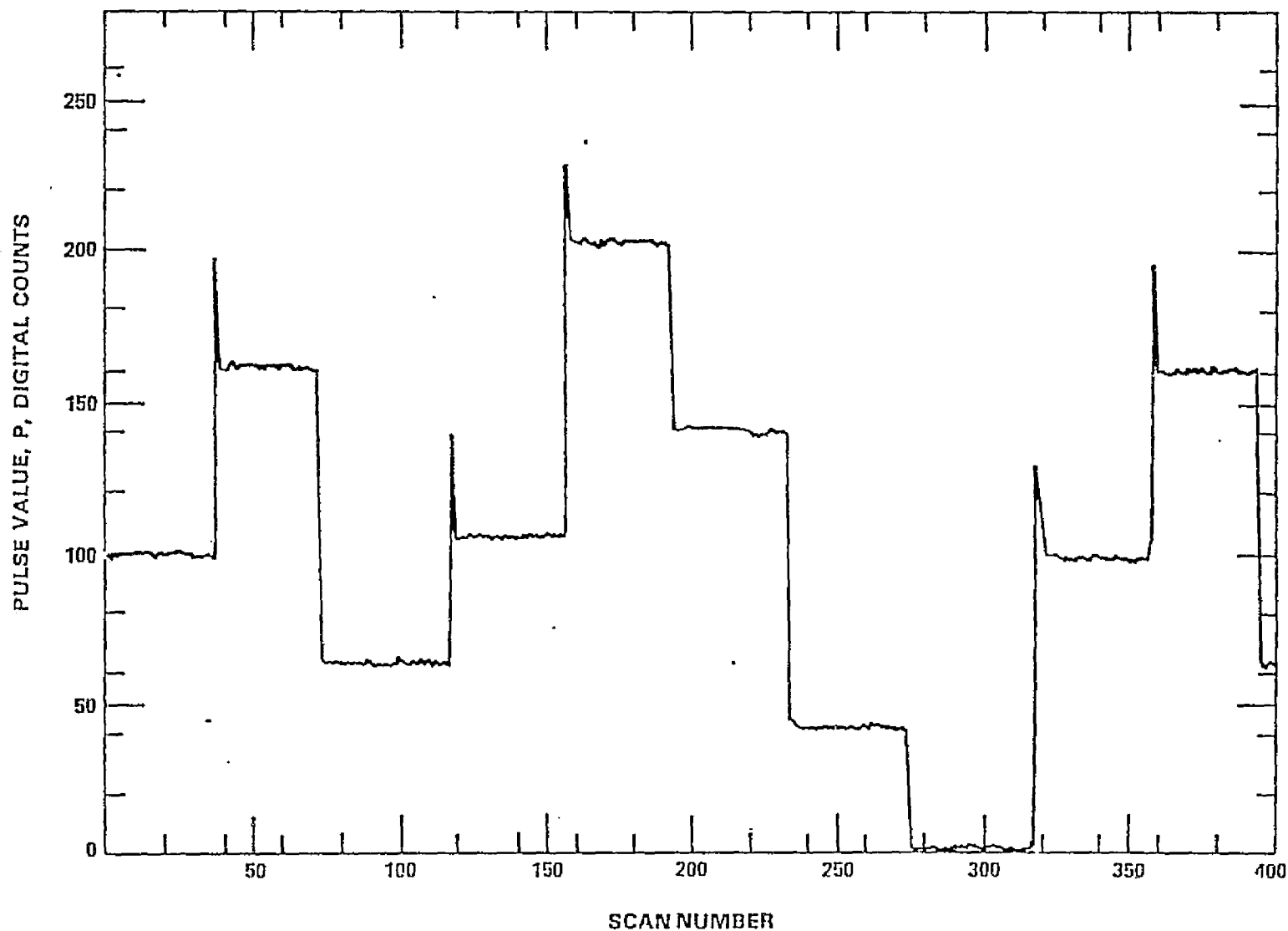
FIGURE A-11  
POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM7 CHANNEL 9, ID = 40109—15140 PULSE VALUES



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FIGURE A-12

**PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4**  
**TM1 CHANNEL 9, MARCH 9, 1982, PULSE VALUES**



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FIGURE A-13

PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM2 CHANNEL 9, MARCH 9, 1982, PULSE VALUES

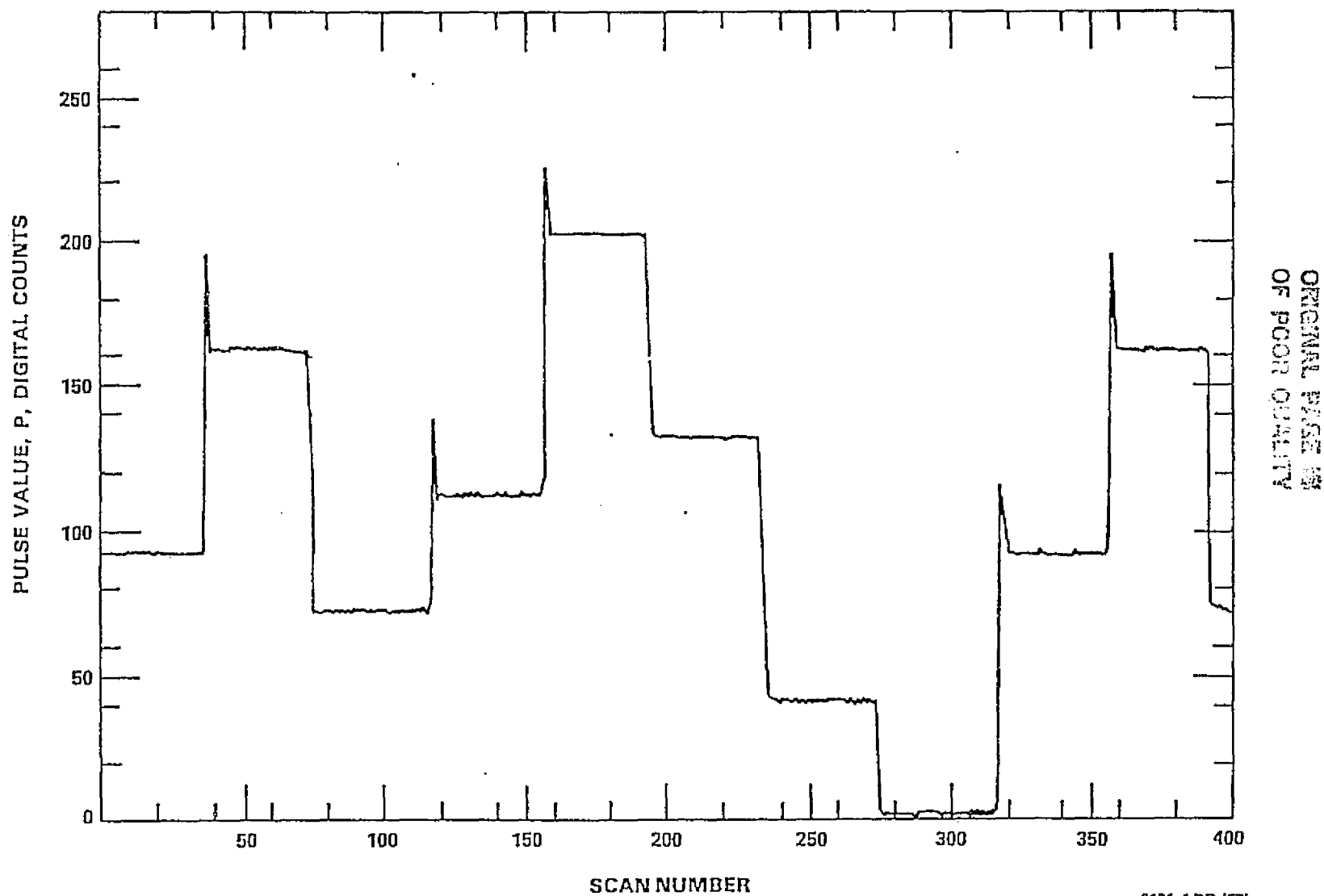
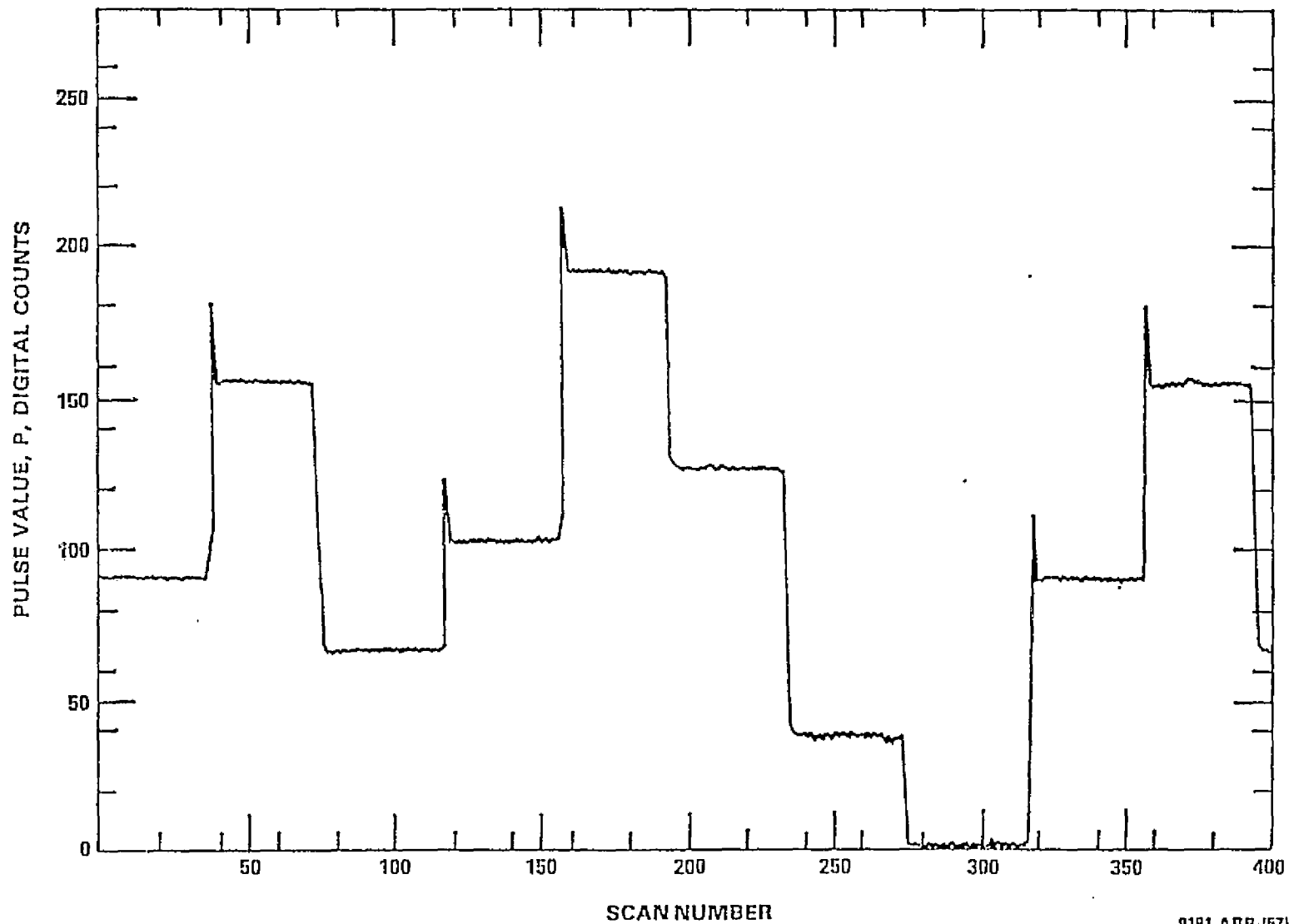


FIGURE A-14

PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM3 CHANNEL 9, MARCH 9, 1982, PULSE VALUES



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FIGURE A-15

PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM4 CHANNEL 9, MARCH 9, 1982, PULSE VALUES

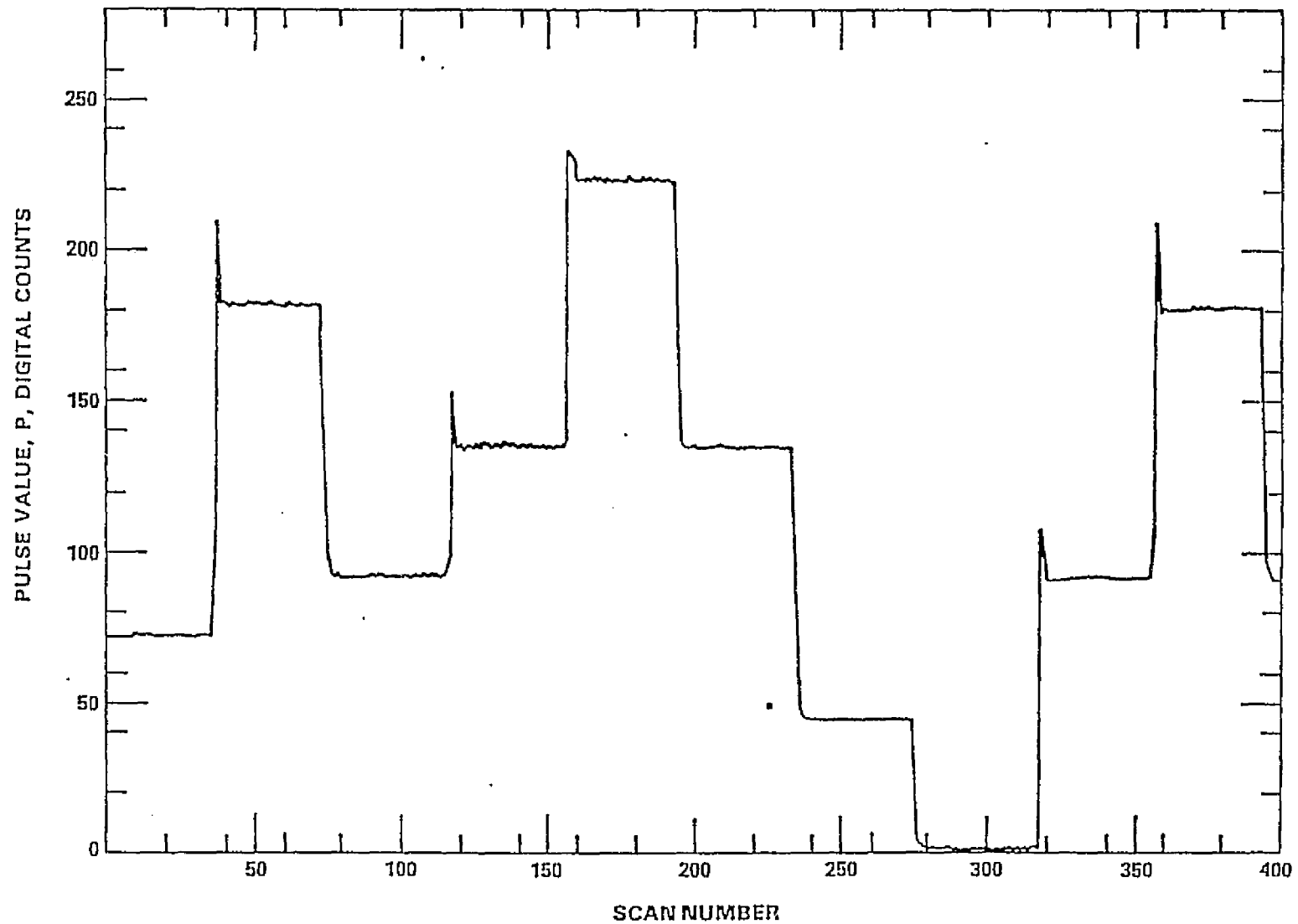
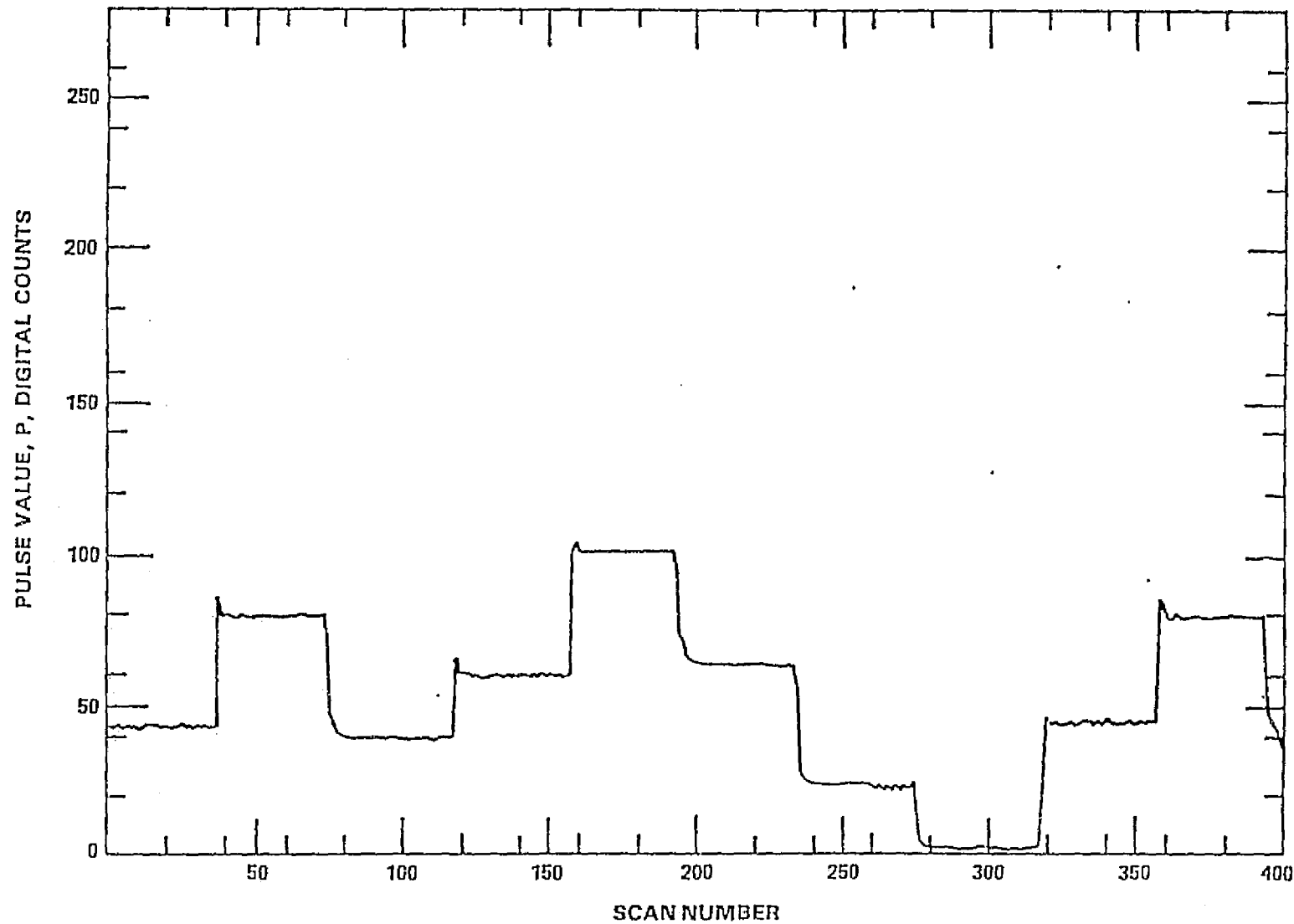


FIGURE A-16

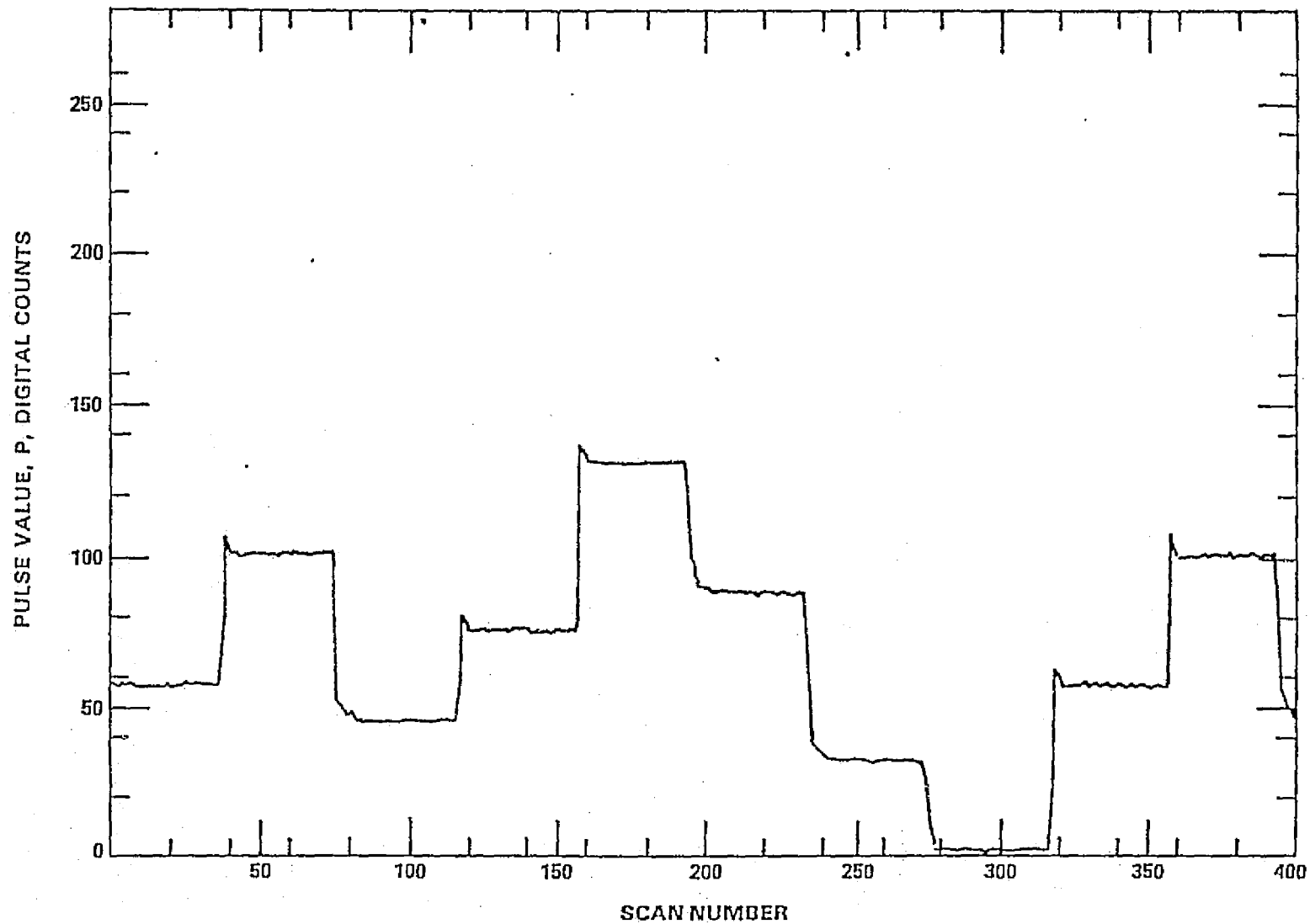
PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM5 CHANNEL 9, MARCH 9, 1982, PULSE VALUES



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FIGURE A-17

PRELAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
TM7 CHANNEL 9, MARCH 9, 1982, PULSE VALUES



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TABLE A-1

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_2$  — PRELAUNCH, VACUUM, MARCH 9, 1982

BAND <sup>a</sup>	$\overline{P}_1$ - NE ARKANSAS, AUGUST 22, 1982			$\overline{P}_1$ - BOSTON, SEPTEMBER 10, 1982		
	IC STATE					
	100	010	001	100	010	001
1O	-3.3	-2.9	-3.6	-4.0	-3.3	-4.2
1E	-3.7	-3.6	-4.1	-4.3	-3.7	-4.4
2O	-2.6	-1.5	-3.1	-3.1	-1.9	-3.7
2E	-3.2	-2.5	-3.3	-3.6	-2.7	-3.6
3O	-3.3	-1.6	-3.1	-4.1	-2.5	-4.2
3E	-3.2	-1.5	-3.1	-4.0	-2.3	-3.9
4O	-1.8	0	-1.7	-2.4	-1.1	-3.6
4E	-1.5	-0.2	-1.5	-2.1	-1.3	-3.3
5O	0	0.7	-0.6	6.9	7.8	6.0
5E	0.4	1.2	-0.2	7.5	8.2	6.7
7O	0.5	3.4	0	-1.9	1.0	-2.3
7E	-0.8	2.4	-0.18	-3.1	0	-2.6

NOTE: <sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-2

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_2$  — PRELAUNCH, VACUUM, MARCH 9, 1982

BAND <sup>a</sup>	$\bar{P}_1$ — FT. DODGE, AUGUST 25, 1982			$\bar{P}_1$ — WASHINGTON, D.C., NOVEMBER 2, 1982		
	IC STATE			IC STATE		
	100	010	001	100	010	001
1O	-3.1	-2.5	-3.4	-5.0	-4.3	-5.4
1E	-3.5	-2.9	-3.7	-5.1	-4.4	-5.4
2O	-2.5	-1.3	-3.1	-3.6	-2.7	-4.4
2E	-2.9	-2.1	-3.1	-3.9	-3.2	-4.0
3O	-3.2	-1.4	-3.2	-5.2	-3.8	-5.4
3E	-3.0	-1.2	-2.8	-5.1	-3.5	-5.1
4O	-1.8	-0.1	-1.8	-3.1	-1.8	-3.6
4E	-1.5	-0.2	-1.5	-3.0	-2.1	-3.4
5O	0.8	1.7	0.2	5.5	6.2	4.6
5E	1.3	2.0	0.4	5.9	6.6	5.1
7O	0.1	2.7	0.0	1.3	3.7	5.4
7E	-1.4	1.7	-1.0	3.0	2.8	2.3

NOTE: O = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-3

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_2$  — PRELAUNCH, VACUUM, MARCH 9, 1982

BAND <sup>a</sup>	$\bar{P}_1$ — HAMILTON, MONTANA, NOVEMBER 24, 1982			$\bar{P}_1$ — FT. PIERCE, FLORIDA, DECEMBER 20, 1982		
	IC STATE			IC STATE		
	100	010	001	100	010	001
1O	-4.3	-4.2	-5.6	-5.5	-4.9	-6.1
1E	-4.6	-4.6	-5.8	-5.8	-5.5	-6.3
2O	-3.1	-2.3	-4.2	-3.7	-2.8	-4.5
2E	-3.6	-3.0	-4.1	-4.3	-3.7	-4.5
3O	-4.8	-3.5	-5.2	-5.8	-4.4	-6.0
3E	-4.7	-3.3	-5.1	-5.7	-4.0	-5.7
4O	-3.4	-1.9	-3.8	-4.0	-2.6	-4.0
4E	-3.2	-2.2	-3.7	-3.8	-3.1	-4.3
5O	-2.5	3.3	1.7	3.1	3.7	2
5E	-3.1	3.8	2.1	3.4	3.9	2.1
7O	9.0	3.5	0.4	3.4	0.1	2.8
7E	-2.5	0.3	-2.4	-0.7	2.3	-0.4

NOTE: <sup>a</sup>0 = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-4

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_2$  — PRELAUNCH, VACUUM, MARCH 9, 1982

BAND <sup>a</sup>	$\bar{P}_1$ — FORMAN, NORTH DAKOTA, SEPTEMBER 24, 1982			$\bar{P}_1$ — OTTAWA, CANADA, OCTOBER 24, 1982		
	IC STATE			IC STATE		
	100	010	001	100	010	001
1O	-4.6	-4.2	-5.1	-5.2	-4.5	-5.4
1E	-5.0	-4.6	-5.4	-5.6	-5.2	-5.7
2O	-3.5	-2.4	-4.1	-3.6	-2.5	-4.2
2E	-4.2	-3.5	-4.2	-4.2	-3.4	-4.1
3O	-5.2	-3.4	-5.1	-5.4	-3.7	-5.4
3E	-5.0	-3.2	-4.9	-5.3	-3.4	-5.0
4O	-2.8	-1.0	-2.7	-3.4	-1.6	-3.4
4E	-2.5	-1.3	-2.6	-3.1	-1.8	-3.2
5O	4.6	5.7	3.9	2.3	3.1	1.5
5E	5.3	6.1	4.5	2.7	3.4	1.8
7O	1.9	5.0	1.5	4.3	7.5	3.9
7E	-1.9	1.4	-1.4	0.5	3.9	1.0

NOTE:  $a_0$  = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-5

# POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4 STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_1$  = DETROIT, JULY 20, 1983

$\bar{P}_2$  = MARCH 9, 1982

BAND <sup>a</sup>	IC STATE		
	100	010	001
1O	0.9	1.3	1.3
1E	-0.1	0.3	0.3
2O	0.6	0.9	0.5
2E	-1.5	-1.6	-1.4
3O	-0.6	1.2	0.2
3E	-0.3	1.9	0.5
4O	0.3	2.4	0.2
4E	0.3	1.2	-0.3

NOTE: a<sub>0</sub> = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-6

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_2 = \text{D.C., NOVEMBER 2, 1982}$

BAND <sup>a</sup>	$\bar{P}_1 = \text{NE ARKANSAS, AUGUST 22, 1982}$			$\bar{P}_1 = \text{BOSTON, SEPTEMBER 10, 1982}$		
	IC STATE			IC STATE		
	100	010	001	100	010	001
1O	1.6	1.5	1.8	1.0	1.0	1.2
1E	1.4	0.8	1.3	0.8	0.6	1.0
2O	1.0	1.3	1.3	0.5	0.8	0.7
2E	0.7	0.8	0.7	0.4	0.8	0.4
3O	1.9	2.2	2.3	1.1	1.3	1.2
3E	1.9	2.1	2.0	1.1	1.2	1.2
4O	1.4	1.8	1.9	0.7	0.7	0
4E	1.6	1.8	1.8	0.9	0.7	0.2
5O	-5.5	-5.5	-5.4	1.4	1.6	1.4
5E	-5.3	-5.2	-5.3	1.5	1.9	1.5
7O	-0.7	-0.3	0.5	-3.1	-2.9	-2.9
7E	-0.8	-0.3	0.1	-3.1	-2.7	-2.7

NOTE:

<sup>a</sup>O = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-7

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_2$  — D.C., NOVEMBER 2, 1982

BAND <sup>a</sup>	$\bar{P}_1$ — FT. DODGE, AUGUST 25, 1982			$\bar{P}_1$ — FOREHAM, NORTH DAKOTA, SEPTEMBER 24, 1982		
	IC STATE			IC STATE		
	100	010	001	100	010	001
1O	1.8	1.9	2.0	0.4	0.1	0.3
1E	1.6	1.5	1.7	0.1	-0.4	-0.1
2O	1.1	1.5	1.3	0.1	0.3	0.2
2E	1.0	1.1	1.0	-0.4	-0.3	-0.2
3O	2.0	2.3	2.2	0.0	-0.3	0.2
3E	2.1	2.3	2.3	0.0	-0.3	0.2
4O	1.5	1.7	1.8	0.3	0.8	0.9
4E	1.5	1.9	1.8	0.5	0.8	0.8
5O	-4.7	-4.9	-4.4	-0.8	-0.5	-0.7
5E	-4.7	-4.4	-4.7	-0.7	-0.5	-0.6
7O	-1.4	-0.9	-1.1	-1.7	-1.0	-1.4
7E	-1.3	-1.0	-1.2	-1.9	-1.3	-1.6

NOTE: <sup>a</sup><sub>O</sub> = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-8

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

%  $(\bar{P}_1 - \bar{P}_2)/\bar{P}_2 = \text{D.C., NOVEMBER 2, 1982}$

BAND <sup>a</sup>	$\bar{P}_1 -$ OTTAWA, CANADA, OCTOBER 24, 1982			$\bar{P}_1 -$ HAMILTON, MONTANA, NOVEMBER 24, 1982		
	IC STATE			IC STATE		
	100	010	001	100	010	001
1O	-0.2	-0.2	-0.1	0.6	0.2	-0.2
1E	-0.5	-0.9	-0.4	0.5	0.3	-0.4
2O	0.0	0.3	0.2	0.4	0.5	-0.2
2E	-0.3	-0.2	-0.1	0.3	0.2	-0.1
3O	-0.2	0.1	0.0	0.4	0.3	0.0
3E	-0.2	0.1	0.1	0.3	0.3	0.0
4O	-0.3	0.2	0.1	-0.3	0.0	-0.2
4E	-0.1	0.2	0.2	-0.2	-0.1	-0.3
5O	-3.3	-3.0	-3.1	-2.4	-2.9	-2.9
5E	-3.3	-3.1	-3.3	-3.1	-2.8	-3.0
7O	0.7	1.5	1.0	-2.7	-2.5	-2.5
7E	0.5	1.2	0.8	-2.5	-2.5	-2.2

NOTE: <sup>a</sup>0 = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-9

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STABILITY OF INTERNAL CALIBRATION SYSTEM

%  $(\bar{P}_1 - \bar{P}_2)/\bar{P}_2 = \text{D.C., NOVEMBER 2, 1982}$

BAND <sup>a</sup>	$\bar{P}_1 -$ MODESSA, CALIFORNIA, DECEMBER 8, 1982			$\bar{P}_1 -$ FT. PIERCE, FLORIDA, DECEMBER 20, 1982		
	IC STATE			IC STATE		
	100	010	001	100	010.	001
1O	0.1	0.3	1.1	-0.5	-0.6	-0.7
1E	0.0	0.0	1.0	-0.7	-1.2	-1.0
2O	0.2	0.4	0.3	-0.1	-0.1	-0.2
2E	0.1	0.3	0.3	-0.4	-0.5	-0.5
3O	0.0	0.1	0.1	-0.6	-0.6	-0.6
3E	0.0	0.1	0.5	-0.6	-0.5	-0.7
4O	-0.3	-0.2	-0.2	-0.9	-0.8	-1.0
4E	-0.5	-0.3	-0.2	-0.8	-0.8	-1.1
5O	-5.3	-5.7	-5.4	-2.4	-2.5	-2.5
5E	-5.9	-5.8	-5.6	-2.6	-2.5	-2.8
7O	-2.0	-1.8	-1.7	-0.3	0.1	-0.2
7E	-2.1	-2.1	-2.2	-0.7	-0.4	-0.6

NOTE: <sup>a</sup><sub>0</sub> = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-10

# POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4 STABILITY OF INTERNAL CALIBRATION SYSTEM

$$\% (\bar{P}_1 - \bar{P}_2) / \bar{P}_2$$

$\bar{P}_1$  = DETROIT, JULY 20, 1983

$\bar{P}_2$  = D.C., NOVEMBER 1982

BAND <sup>a</sup>	IC STATE		
	100	010	001
10	5.9	3.0	6.7
1E	5.0	4.1	5.6
20	4.2	3.7	4.9
2E	2.3	1.6	2.6
30	4.7	5.0	5.6
3E	4.8	5.4	5.6
40	2.8	4.1	3.7
4E	2.8	3.3	3.1

NOTE: a<sub>0</sub> = ODD DETECTORS; E = EVEN DETECTORS.

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TABLE A-11

**POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4**  
**TM2 CHANGE IN GAIN (ppt) RELATIVE TO MARCH 9, 1982**

CHANNEL	DATE				
	AUGUST 22	SEPTEMBER 10	OCTOBER 24	NOVEMBER 24	DECEMBER 8
1	-23	-27	-32	-31	-32
2	-34	-36	-43	-40	-40
3	-22	-27	-32	-31	-31
4	-6	-9	-17	-17	-16
5	-22	-26	-31	-30	-31
6	-33	-36	-42	-39	-40
7	-23	-28	-34	-31	-32
8	-34	-37	-44	-41	-40
9	-23	-28	-33	-32	-33
10	-34	-37	-43	-39	-40
11	-24	-29	-34	-32	-33
12	-34	-37	-43	-40	-39
13	-23	-27	-32	-31	-32
14	-33	-37	-42	-39	-41
15	-23	-28	-34	-32	-33
16	-34	-36	-43	-41	-40
MEAN	-26.6	-30.3	-36.0	-34.1	-34.6
SD	7.7	7.3	7.2	6.3	6.3

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TABLE A-12

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
 TM5 CHANGE IN GAIN (ppt) RELATIVE TO MARCH 9, 1982

CHANNEL	DATE				
	AUGUST 22	SEPTEMBER 10	OCTOBER 24	NOVEMBER 24	DECEMBER 8
1	19	87	36	55	19
2	23	93	42	59	22
3	—	—	—	—	—
4	-9	61	12	20	-11
5	-14	52	6	12	-16
6	6	78	29	32	3
7	2	73	26	27	0
8	8	80	33	33	7
9	0	69	23	22	-2
10	-8	60	16	12	-11
11	1	71	25	23	0
12	6	77	32	28	3
13	2	71	26	24	0
14	7	78	31	30	4
15	-4	62	17	20	-7
16	17	87	40	43	14
MEAN	3.7	73.3	26.0	29.3	1.66
SD	10.4	11.4	10.2	13.8	10.8

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TABLE A-13

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
 TM7 CHANGE IN GAIN (ppt) RELATIVE TO MARCH 9, 1982

CHANNEL	DATE				
	AUGUST 22	SEPTEMBER 10	OCTOBER 24	NOVEMBER 24	DECEMBER 8
1	23	0	39	4	8
2	9	-14	22	-9	-7
3	16	-7	31	-3	1
4	0	-22	14	-19	-15
5	0	-22	16	-19	-12
6	1	-20	15	-18	-12
7	85	158	203	160	170
8	-11	-33	2	-30	-25
9	15	-8	30	-4	4
10	11	-11	25	-8	-2
11	13	-10	29	-7	1
12	11	-11	24	-9	-3
13	12	-11	28	-7	0
14	-6	-28	7	-26	-20
15	6	-17	21	-13	-6
16	18	-3	33	0	4
MEAN	18.9	-2.6	34.0	-0.5	7.9
SD	45.2	45.6	46.1	43.8	44.4

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TABLE A-14

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STANDARD DEVIATION OF BACKGROUND,  
WASHINGTON, D.C., NOVEMBER 2, 1982  
(DIGITAL COUNTS)

CHANNEL		TM1	TM2	TM3	TM4	TM5	TM7
{	1	1.28	0.50	0.79	0.47	0.80	0.98
	2	1.44	1.00	0.54	0.38	0.75	0.99
	3	1.19	0.49	0.57	0.48	—	0.85
	4	1.44	0.69	0.72	0.38	0.82	1.03
	5	1.08	0.43	0.53	0.30	0.87	0.91
	6	1.43	0.52	0.52	0.48	0.88	1.01
	7	1.26	0.37	0.49	0.25	1.08	1.94
	8	1.31	0.42	0.35	0.53	0.81	0.92
	9	1.09	0.30	0.45	0.24	0.85	0.96
	10	1.18	0.30	0.57	0.32	0.87	1.05
	11	1.24	0.35	0.39	0.25	0.91	0.93
	12	1.32	0.37	0.47	0.41	0.84	1.00
	13	1.14	0.35	0.52	0.20	0.83	0.80
	14	1.35	0.36	0.59	0.26	0.79	1.09
	15	1.26	0.34	0.51	0.25	0.82	0.78
	16	1.60	0.43	0.84	0.41	0.78	0.95
MEANODD		1.19	0.39	0.53	0.31	0.88	1.02
MEANENVN		1.38	0.51	0.64	0.39	0.82	1.00
MEANALL		1.29	0.45	0.59	0.35	0.85	1.01
MEANODD SD		0.08	0.07	0.11	0.10	0.09	0.37
MEANENVN SD		0.12	0.23	0.14	0.08	0.04	0.05
MEANALL SD		0.14	0.17	0.14	0.10	0.07	0.26
MEANALL CV		10.86	38.94	23.72	29.21	9.05	25.72

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TABLE A-15

POSTLAUNCH RADIOMETRIC CALIBRATION — TM LANDSAT-4  
STANDARD DEVIATION OF BACKGROUND, MARCH 9, 1982  
(DIGITAL COUNTS)

CHANNEL		TM1	TM2	TM3	TM4	TM5	TM7
{	1	1.37	0.49	0.69	0.45	0.89	1.10
	2	1.44	1.02	0.53	0.41	0.89	1.12
	3	1.23	0.52	0.56	0.49	—	1.03
	4	1.00	0.65	0.77	0.43	0.84	1.14
	5	1.18	0.47	0.54	0.34	0.93	1.01
	6	1.40	0.54	0.53	0.49	1.16	1.12
	7	1.12	0.42	0.52	0.29	1.08	2.85
	8	1.32	0.46	0.88	0.56	0.85	1.05
	9	1.15	0.39	0.50	0.30	0.93	1.09
	10	1.00	0.40	0.58	0.34	0.96	1.20
	11	1.30	0.44	0.42	0.29	0.98	1.05
	12	0.99	0.39	0.53	0.29	0.95	1.14
	13	1.19	0.42	0.54	0.22	0.89	0.92
	14	1.35	0.44	0.64	0.30	0.92	1.17
	15	1.31	0.41	0.52	0.25	0.91	0.90
	16	1.65	0.51	0.86	0.38	0.90	1.08
MEANODD		1.23	0.45	0.53	0.33	0.94	1.24
MEANEVN		1.27	0.55	0.66	0.40	0.93	1.13
MEANALL		1.25	0.50	0.60	0.36	0.94	1.19
MEANODD SD		0.08	0.04	0.07	0.09	0.06	0.65
MEANEVN SD		0.24	0.20	0.14	0.09	0.10	0.04
MEANALL SD		0.18	0.15	0.13	0.09	0.08	0.45
MEANALL CV		14.36	30.99	21.90	26.88	8.95	37.85

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TABLE A-16

PROTOFLIGHT TM1, CHANNEL 1 A/D CONVERTER BIN SIZES<sup>a</sup> (1 OF 5)

DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE		DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE	
			CALCULATED (mV)	DEVIATION				CALCULATED (mV)	DEVIATION
0	-46.6		-45.3	-1.3	27	387.6	16.5	382.8	4.8
1	-30.9	15.7	-29.4	-1.4	28	400.2	12.6	398.7	1.5
2	-10.2	20.6	-13.6	3.4	29	420.7	20.5	414.5	6.2
3	0.0	10.3	2.3	-2.2	30	436.8	16.1	430.4	6.5
4	19.6	10.5	18.1	1.4	31	441.3	4.4	446.2	-4.9
5	37.5	17.9	34.0	3.5	32	460.9	19.7	462.1	-1.1
6	56.2	18.7	49.8	6.4	33	476.4	15.4	477.9	-1.6
7	63.4	7.1	65.7	-2.3	34	497.5	21.1	493.8	3.7
8	81.0	17.6	81.5	-0.6	35	507.6	10.1	509.6	-2.0
9	98.7	17.7	97.4	1.3	36	526.7	19.1	525.5	1.2
10	117.4	18.6	115.3	4.1	37	544.5	17.7	541.4	3.1
11	131.6	14.3	129.1	2.5	38	563.3	18.8	557.2	6.1
12	146.9	15.2	145.0	1.9	39	573.7	10.3	573.1	0.6
13	167.0	20.1	160.8	6.1	40	587.9	14.3	588.9	-1.0
14	183.2	16.3	176.7	6.6	41	605.5	17.5	604.8	0.7
15	192.7	9.5	192.5	0.2	42	624.6	19.2	620.6	4.0
16	207.5	14.7	208.4	-0.9	43	638.7	14.0	636.5	2.2
17	223.1	15.7	224.2	-1.1	44	653.5	14.9	652.3	1.2
18	243.5	20.4	240.1	3.4	45	673.5	19.9	668.2	5.3
19	256.4	12.8	256.0	0.4	46	690.0	16.5	684.1	5.9
20	273.3	17.0	271.8	1.5	47	702.9	12.9	699.9	3.0
21	291.4	18.0	287.7	3.7	48	713.7	10.7	715.8	-2.1
22	309.8	18.4	303.5	6.3	49	729.5	15.8	731.6	-2.1
23	320.7	10.9	319.4	1.3	50	749.7	20.2	747.5	2.3
24	334.4	13.7	335.2	-0.8	51	762.8	13.0	763.3	-0.6
25	352.5	18.1	351.1	1.4	52	779.2	16.4	779.2	0.0
26	371.1	18.5	366.9	4.1	53	797.3	18.1	795.0	2.3

<sup>a</sup>MEASUREMENT ON NOVEMBER 15, 1980.

TABLE A-16

PROTOFLIGHT TM1, CHANNEL 1 A/D CONVERTER BIN SIZES<sup>a</sup> (2 OF 5)

DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE		DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE	
			CALCULATED (mV)	DEVIATION				CALCULATED (mV)	DEVIATION
54	815.7	18.4	810.9	4.8	81	1235.0	15.3	1239.0	-4.0
55	829.7	14.0	826.8	3.0	82	1255.7	20.7	1254.9	0.8
56	840.2	10.4	842.6	-2.5	83	1267.7	12.0	1270.7	-3.0
57	858.0	17.9	858.5	-0.4	84	1284.9	17.2	1286.6	-1.6
58	876.8	18.8	874.3	2.5	85	1302.6	17.6	1302.4	0.2
59	893.3	16.5	890.2	3.1	86	1321.3	18.7	1318.3	3.0
60	905.6	12.2	906.0	-0.5	87	1333.3	12.0	1334.1	-0.8
61	925.7	20.2	921.9	3.9	88	1348.2	12.9	1350.0	-3.8
62	942.0	16.3	937.7	4.3	89	1363.4	17.2	1365.8	-2.4
63	952.1	10.1	953.6	-1.5	90	1381.9	18.5	1381.7	0.2
64	967.4	15.3	969.5	-2.0	91	1401.3	19.4	1397.6	3.8
65	982.3	14.8	985.3	-3.0	92	1411.4	10.1	1413.4	-2.0
66	1003.3	21.1	1001.2	2.2	93	1431.3	19.9	1429.3	2.1
67	1012.9	9.5	1017.0	-4.2	94	1447.8	16.4	1445.1	2.7
68	1033.0	20.2	1032.9	4.2	95	1460.1	12.3	1461.0	-0.9
69	1050.0	17.0	1048.7	1.3	96	1471.9	11.8	1476.8	-4.9
70	1069.1	19.1	1064.6	4.5	97	1486.7	14.8	1492.7	-6.0
71	1077.0	7.9	1080.4	-3.4	98	1507.9	21.2	1508.5	-0.6
72	1094.0	16.9	1096.3	-2.3	99	1517.6	9.7	1524.4	-6.8
73	1111.1	17.1	1112.2	-1.0	100	1537.4	19.8	1540.3	-2.8
74	1130.9	19.8	1123.0	7.9	101	1554.3	16.8	1556.1	-1.8
75	1143.5	12.6	1143.9	-0.3	102	1573.7	19.5	1572.0	1.8
76	1159.5	15.9	1159.7	-0.3	103	1593.8	10.1	1587.8	4.0
77	1178.9	19.5	1175.8	3.4	104	1599.7	14.8	1603.7	-5.0
78	1195.8	16.9	1191.4	4.4	105	1615.4	16.7	1619.5	-4.2
79	1208.5	12.6	1207.3	1.2	106	1634.6	19.2	1635.4	-0.8
80	1219.6	11.2	1223.1	-3.5	107	1652.0	17.4	1651.2	0.8

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TABLE A-16

PROTOFLIGHT TM1, CHANNEL 1 A/D CONVERTER BIN SIZES<sup>a</sup> (3 OF 5)

DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE		DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE	
			CALCULATED (mV)	DEVIATION				CALCULATED (mV)	DEVIATION
108	1663.9	11.9	1667.1	-3.2	135	2090.3	5.5	2095.2	-4.9
109	1683.2	19.3	1683.0	0.2	136	2106.1	15.8	2111.0	-5.0
110	1700.3	17.1	1698.8	1.5	137	2124.5	18.4	2126.9	-2.4
111	1716.7	16.4	1714.7	2.0	138	2144.9	20.4	2142.3	2.1
112	1724.0	7.3	1730.5	-6.5	139	2161.8	17.0	2158.6	3.2
113	1739.1	15.1	1746.4	-7.3	140	2171.6	9.7	2174.5	-2.9
114	1760.0	20.9	1762.2	-2.3	141	2196.0	24.4	2190.3	5.7
115	1772.2	12.2	1778.1	-5.9	142	2212.5	16.4	2206.2	6.3
116	1789.4	17.2	1793.9	-4.6	143	2220.8	8.4	2222.0	-1.2
117	1806.8	17.4	1809.8	-3.0	144	2232.1	11.3	2237.9	-5.8
118	1825.7	18.9	1825.7	0.0	145	2248.2	16.1	2253.7	-5.5
119	1840.2	14.5	1841.5	-1.3	146	2269.6	21.3	2269.6	-0.0
120	1850.5	10.3	1857.4	-6.8	147	2281.5	12.0	2285.5	-3.9
121	1867.4	16.9	1873.2	-5.8	148	2297.6	16.0	2301.3	-3.7
122	1886.3	18.9	1880.1	-2.8	149	2319.0	21.4	2317.2	1.8
123	1902.6	16.3	1904.9	-2.3	150	2337.2	18.2	2333.0	4.1
124	1915.8	13.3	1920.8	-4.9	151	2348.0	10.8	2348.9	-0.9
125	1935.3	19.4	1936.6	-1.4	152	2358.5	10.5	2364.7	-6.3
126	1951.6	16.5	1952.5	-0.7	153	2377.1	18.7	2380.6	-3.5
127	1965.2	13.4	1968.4	-3.2	154	2397.2	20.0	2396.4	0.7
128	1979.6	14.4	1984.2	-4.6	155	2417.7	20.5	2412.3	5.4
129	1995.7	16.1	2000.1	-4.3	156	2423.8	6.1	2428.2	-4.3
130	2017.2	21.4	2015.9	1.2	157	2450.0	26.1	2444.0	6.0
131	2031.9	14.7	2031.8	0.1	158	2464.8	14.8	2459.9	4.9
132	2045.2	13.3	2047.6	-2.4	159	2468.1	3.3	2475.7	-7.7
133	2065.4	20.2	2063.5	1.9	160	2484.5	16.4	2491.6	-7.1
134	2084.8	19.4	2079.3	5.5	161	2500.5	16.0	2507.4	-7.0

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TABLE A-16

PROTOFLIGHT TM1, CHANNEL 1 A/D CONVERTER BIN SIZES<sup>a</sup> (4 OF 5)

DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE		DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE	
			CALCULATED (mV)	DEVIATION				CALCULATED (mV)	DEVIATION
162	2522.3	21.8	2523.3	-1.0	189	2955.5	26.1	2951.4	4.1
163	2531.8	9.5	2539.1	-7.3	190	2970.2	14.7	2967.2	2.9
164	2550.0	18.2	2555.0	-5.0	191	2980.9	10.8	2983.1	-2.2
165	2568.2	18.2	2570.9	-2.7	192	2996.2	15.3	2999.0	-2.7
166	2589.8	21.6	2586.7	3.1	193	3007.2	11.0	3014.8	-7.6
167	2598.6	8.8	2602.6	-4.0	194	3029.3	22.1	3030.7	-1.3
168	2611.1	12.5	2618.4	-7.3	195	3043.3	13.9	3046.5	-3.3
169	2629.1	18.0	2634.3	-5.1	196	3057.7	14.4	3062.4	-4.7
170	2649.8	20.7	2650.1	-0.3	197	3075.2	17.5	3078.2	-3.1
171	2667.5	17.7	2666.0	1.5	198	3097.1	21.9	3094.1	3.0
172	2676.9	9.4	2681.8	-5.0	199	3102.6	5.5	3109.9	-7.4
173	2700.7	23.8	2697.7	3.0	200	3119.0	16.4	3125.8	-6.8
174	2717.4	16.7	2713.6	3.8	201	3136.9	17.9	3141.7	-4.7
175	2729.0	11.6	2729.4	-0.4	202	3157.7	20.8	3157.5	0.2
176	2737.3	8.3	2745.3	-8.0	203	3175.1	17.3	3173.4	1.7
177	2753.1	15.8	2761.1	-8.1	204	3184.9	9.8	3189.2	-4.3
178	2774.5	21.5	2777.0	-2.4	205	3209.2	24.3	3205.1	4.1
179	2786.7	12.2	2792.8	-6.1	206	3225.9	16.7	3220.9	5.0
180	2802.8	16.0	2808.7	-5.9	207	3238.0	12.0	3236.8	1.2
181	2823.9	21.1	2824.5	-0.7	208	3245.8	7.9	3252.6	-6.8
182	2842.3	18.4	2840.4	1.9	209	3261.8	16.0	3268.5	-6.7
183	2858.0	15.7	2856.3	1.7	210	3283.8	22.0	3284.4	-0.5
184	2863.8	5.8	2872.1	-8.3	211	3295.1	11.3	3300.2	-5.1
185	2882.1	18.3	2888.0	-5.8	212	3312.2	17.1	3316.1	-3.9
186	2902.6	20.4	2903.8	-1.3	213	3331.3	19.1	3331.9	-0.7
187	2924.0	21.4	2919.7	4.3	214	3351.9	20.6	3347.8	4.1
188	2929.4	5.4	2935.5	-6.2	215	3361.5	12.6	3363.6	0.9

TABLE A-16

PROTOFLIGHT TM1, CHANNEL 1 A/D CONVERTER BIN SIZES<sup>a</sup> (5 OF 5)

DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE		DIGITAL COUNT LEVEL	MEASURED INPUT (mV)	INCREASE FROM PREVIOUS THRESHOLD (mV)	BEST FIT STRAIGHT LINE	
			CALCULATED (mV)	DEVIATION				CALCULATED (mV)	DEVIATION
216	3373.8	9.3	3379.5	-5.7	236	3696.9	9.9	3696.6	0.3
217	3392.0	18.2	3395.3	-3.3	237	3721.1	24.2	3712.5	8.6
218	3412.8	20.8	3411.2	1.6	238	3737.9	16.8	3728.3	9.6
219	3431.4	20.6	3427.1	6.4	239	3752.6	14.7	3744.2	8.5
220	3439.8	6.4	3442.9	-3.1	240	3766.2	13.6	3760.0	6.2
221	3465.7	25.8	3458.8	6.9	241	3773.9	7.7	3775.9	-2.0
222	3481.2	15.5	3474.6	6.6	242	3800.0	26.1	3791.7	8.2
223	3492.1	10.9	3490.5	1.6	243	3807.8	7.8	3807.6	0.2
224	3508.8	16.7	3506.3	2.5	244	3825.0	17.2	3823.4	1.6
225	3517.1	8.3	3522.2	-5.0	245	3846.1	21.1	3839.3	6.8
226	3539.4	22.2	3538.0	1.3	246	3865.0	18.9	3855.2	9.9
227	3548.7	9.3	3553.9	-5.2	247	3882.4	17.4	3871.0	11.4
228	3568.1	19.4	3569.8	-1.7	248	3887.1	4.7	3886.9	0.3
229	3585.6	17.5	3585.6	-0.0	249	3905.2	18.0	3902.7	2.4
230	3607.9	22.4	3601.5	6.5	250	3926.4	21.2	3918.6	7.8
231	3617.2	9.2	3617.3	-0.1	251	3948.1	21.7	3934.4	13.6
232	3630.4	13.2	3633.2	-7.8	252	3954.2	6.1	3950.3	3.9
233	3647.8	17.4	3649.0	-1.2	253	3979.9	25.7	3966.1	13.8
234	3668.9	21.1	3664.9	4.0	254	3994.1	14.1	3982.0	12.1
235	3687.0	18.1	3680.7	6.2					

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